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SCHOOL OF SCIENCE

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RE: Final Report

I have enclosed five copies of the final report for Grant No. RMRS-99188-CCS entitled "Tracing the Origin of Sources of Water that Support Streamflow and Riparian Vegetation in High Altitude Watersheds of Central Nevada" for your review.

The title was changed from the original proposal to reflect the nature of the results that were obtained in the study. Also, hydrogen isotopes were not measured as part of the study even though it was called for in the proposal. This was because the information from hydrogen isotopes would have been similar to oxygen isotopes. Instead, additional stable carbon isotope analyses were conducted, since it was more useful in elucidating the sources of water in the study area.

I hope the results of this study provide a better understanding of the hydrology of riparian meadow settings. I look forward to your comments after your review of the report.

Sincerely,

Eliot A. Atekwana

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SUMMARY

In high altitude watersheds in the Great Basin of central Nevada, dry, mesic and wet meadows occur within valleys especially along streams. These riparian corridors encompass less that 2% of the land area, but contain most of the biodiversity. Stream diversion and other forms of hydrologic manipulation in these watersheds can have dramatic effects on instream flows and alter riparian and meadow ecosystems. The nature and extent to which vegetation is affected by hydrologic manipulation in these watersheds will depend on the source or sources of water that support the riparian and meadow ecosystems. Therefore the objective of this study was to determine the source(s) of water (groundwater or surface water) that support high altitude meadow vegetation in two locations: Big Creek in the Toiyabe Range and Corral Canyon in the Toquima Range. Both of these watersheds are located in central Nevada.

The source(s) of water that supports meadow vegetation in the selected meadow complexes was assessed using physical water parameters, conservative tracers (stable oxygen isotopes and chloride), reactive tracers (stable isotope ratio of dissolved inorganic carbon and major ions) and radiocarbon (carbon-14). Shallow groundwater and runoff from the meadow complexes were compared to stream water, seeps, and springs within each watershed. Sampling for geochemical and isotopic analyses was conducted in November 1998, July 1999, and June 2000.

Water from Big Creek watershed was Ca-HCO_3, Mg-HCO_3 or mixed (Ca + Mg + Na) cation-HCO_3 type. Stable oxygen isotope values for water in the watershed ranged from –17.3 to –15.7 $^0/_{00}$, with a mean of -16.5 $\pm$ 0.4 $^0/_{00}$ (with respect to SMOW). The carbon isotopic and radiocarbon values ranged from -15.6 to -7.0 $^0/_{00}$, with a mean of -10.5 $\pm$ 2.0 $^0/_{00}$ (with respect to PDB) and 35 to 99.6 Percent Modern Carbon (PMC), respectively.

Water from Corral Canyon watershed was a mixed (Ca + Mg + Na) cation-HCO_3 type. Stable oxygen isotopes values for water in the watershed ranged from-17.9 to -15.6 $^0/_{00}$, with a mean of -17.0 $\pm$ 0.5 $^0/_{00}$ (with respect to SMOW). The carbon isotopic values ranged from -15.6 to -4.0 $^0/_{00}$, with a mean of -14.4 $\pm$ 2.9 $^0/_{00}$ (with respect to PDB).

The oxygen isotopic data suggests that water in both watersheds was locally derived from snowmelt. In each of the study areas, the major ion data was not able to distinguish between the source of shallow groundwater in the meadow complexes, stream water, seeps and springs. Spatial analyses of physical water parameters, major ion and carbon isotopic data conducted for Big Creek stream showed that there were significant differences between stream water and groundwater from the meadow complex. Although the number of stream segments sampled from the Corral Canyon watershed was limited, stream water flowing through the meadow complex was similar to groundwater, especially during periods of high groundwater levels.

Combined major ion and isotopic models support the hypothesis that there are two primary sources of water supporting the meadow complexes. At the Big Creek, the sources of water included groundwater locally derived from the side valley, and groundwater recharged locally from an upgradient alluvial fan. At Corral Canyon the sources of water included groundwater from the alluvial valley upgradient of the site and local recharge from side valley alluvial fans.

The results of this study suggest that the source of water supporting the meadow complexes is exclusively groundwater. However, hydrologic manipulations that affect stream water levels are expected to impact groundwater levels in the meadow complexes. Because of the dynamic (physical) balance between groundwater levels and stream stage, reduction in stream stage will potentially cause lowering of groundwater levels in the meadow complexes with serious consequences for meadow ecosystem change and vegetation survival.

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INTRODUCTION

Within upland watersheds of the Great Basin of central Nevada, dry, mesic and wet meadow (meadow complex) and other vegetation along riparian corridors encompass less that 2% of the land area, but contain most of the biodiversity (Miller et al, 2000, Jewett, 2000). Riparian corridors provide habitat for a variety of neotropical migrants (e.g. Saab and Groves 1992), numerous endemics, and a relatively high proportion of endangered species (e.g. Hubbard, 1977). Meadow complexes in the high altitudes of the central Great Basin tend to consist mostly of narrow strips along stream channels. The meadow complexes are densely vegetated with grasses, sedges, rushes, and hydrophyllic trees such as willow and river birch, making them prime areas for grazing and for recreational activities (e.g. Martin and Chambers, 2001).

The areal extent of riparian areas and wet meadows in the central Great Basin has decreased over time, and significant changes in the vegetation composition in riparian areas have been documented (Chambers et al. 1998; Martin and Chambers, 2001). Land managers are now charged with managing diverse, productive, and sustainable riparian ecosystems (Chambers, 1994), which require knowledge of both riparian ecosystem function, and management options for maintaining and restoring ecosystem integrity. The lack of understanding of the functional processes within riparian ecosystems has slowed the development of meaningful management objectives, and increased conflicts between managers and increasingly diverse land users in this region.

Stream diversions and other forms of hydrologic manipulation in high altitude watersheds in the Great Basin of central Nevada potentially have dramatic effects on instream flows and the adjacent riparian ecosystems, including meadow complexes. Although changes in riparian vegetation can be attributed to long term climate change, anthropogenic disturbances such as mining, livestock grazing, stream diversion, the presence of roads in valley bottoms, and manipulation of upland vegetation may also be responsible for the observed changes (Chambers et al., 1999; Martin and Chambers, 2001). The general effects of disturbance on riparian ecosystems are relatively well understood, however the linkage between the severity of riparian ecosystem degradation and changes in hydrologic regime, soil properties, and vegetative characteristics is poorly understood (Chambers, 1994).

PROJECT OBJECTVE AND GOALS

Studies of vegetation water relations suggest that soil moisture gradient and depth to water table are important variables that determine the type and distribution of vegetation in meadow complexes in the high altitude watersheds in Central Nevada (Chambers et al., 1999; Castelli et al., 2000). Meadow complexes occur at broad valley bottoms adjacent to perennial streams and generally upgradient of side valley alluvial fans (Chambers et al., 1999; Miller and Jewett, 2000; Martin and Chambers, 2001).

The high altitude setting, the proximity of meadow complexes to perennial streams and possible geomorphic control on the groundwater hydrology make determining the source(s) of water that support meadow complexes difficult. The dominant form of precipitation in Central Nevada upland watersheds is snow, yet it is not

clear whether meadow complexes are supported by direct precipitation, groundwater from side valley alluvial fans, groundwater the valley fill upgradient of the meadow complexes, or by influx of water from adjacent streams.

The objective of this study was to determine the source(s) of water that support high altitude riparian meadow complexes in the central Great Basin in Nevada. The project goal was to conduct chemical, stable isotope, and radio carbon analyses of stream water, shallow groundwater in meadow complexes, runoff from the meadow complexes, seeps and springs in and near meadow complexes, and seeps and springs within the entire watershed to:

1. determine the importance of stream and groundwater as sources of water that support riparian meadow complexes, and
2. quantify the relative source contribution of stream and groundwater in supporting meadow vegetation.

BACKGROUND

Detailed studies of plant-soil water relations suggest that depth to soil water is an important component in determining nutrient status and the type and extent of meadow vegetation development in the central Great Basin (Chambers et al., 1999; Castelli et al., 2000). This observation is consistent with other studies that emphasize the role of hydrology in wetland vegetation development (e.g. Shedlock et al., 1993; Reed, 1993; Rosenberrey et al., 2000). Most of the meadow complexes in high altitude watersheds in the central Great Basin are unique because their geomorphic position in the landscape appears to be controlled by the development of side valley alluvial fans (e.g. Chambers et al., 1999; Miller and Jewett, 2000).

The dominant form of precipitation in the high elevations of the central Great Basin is snow (Castelli et al., 2000; Martin and Chambers, 2001). Water that supports meadow vegetation in these settings could be derived directly from precipitation, or indirectly from stream flooding, stream outflow, or hillslope inflow or recharge from side valley alluvial fans. Direct precipitation and snowmelt can support wet meadow vegetation if the soils in channel floodplain or valley bottom have a relatively impermeable layer, typically clay, which traps water or causes ponding of water at or near the surface. Stream water as a hydrologic source for meadow complex development can result from high stream stage associated with peak snowmelt or large storm events, which cause flooding. Soils in mountainous regions are typically thin and generally overlie less permeable bedrock. Thus infiltrated water moves downgradient on hillslopes towards the valley, discharging within stream channels and along the valley sides as springs and seeps. Groundwater flow from hillslopes and alluvial fans can also support meadow vegetation indirectly from melting of snow packs.

The extent to which vegetation in riparian and meadow complexes is altered by stream water withdrawals and/or stream diversion depends on the role of stream water in supporting these ecosystems. To determine the minimum instream flow required to support riparian and wet meadow vegetation adjacent to streams, Miller and Jewett, (2000) and Jewett (2000) used hydrometric techniques to investigate the relationship between stream water and groundwater in meadow complexes for selected watersheds in

the central Great Basin. The results from Big Creek watershed suggested potential stream water contribution to the meadow complex upgradient of the site (Miller and Jewett, 2000). In another meadow complex investigated in the Corral Canyon watershed, hydrometric measurements suggested a predominant groundwater source (Miller and Jewett, 2000; Jewett, 2000). However, the hydrologic system at the Corral Canyon meadow site was relatively complex, and may have a possible water source from a lower confined aquifer, or from the side valley alluvial fans (Miller and Jewett, 2000).

Hydrometric results from these two meadow complexes are difficult to interpret because of the complexities associated with geomorphological and geological influence on groundwater flow. Modeling stream stage/discharge and groundwater levels in meadow complexes are complicated by the differences in the temporal and spatial flow characteristics of groundwater and surface water. In fact, a recent study using standpipe piezometers to measure water levels in wetland soils, Hanschke and Baird (2001) showed that considerable errors could occur because of time lag response of water levels in sediments with variable hydraulic character. Hanschke and Baird (2001) suggested that these errors could lead to incorrect conclusions about patterns and rates of groundwater flow in wetland soils. In addition, water levels in meadow complexes may be affected by vegetative evapotranspiration, making it difficult to model water levels without accounting for deferential vegetative drawdown on shallow groundwater levels.

Isotopic and geochemical techniques offer a complementary approach to investigate the source of water that support riparian and meadow vegetation. Isotopic and geochemical characteristics of water are developed over a much longer time scale compared to short-term hydrometric response of stream discharge and groundwater levels. Thus, isotopic and geochemical techniques can allow for assessing possible sources of water in streams and shallow groundwater, and to trace the geochemical and isotopic evolution of shallow groundwater in meadow complexes.

Isotopic and geochemical tracers can be divided into two main groups; conservative and reactive tracers. Stable oxygen (and deuterium) isotopes are conservative tracers because the isotopic composition of water in a watershed can be traceable to precipitation events, and is unaffected by biogeochemical processes occurring during water flow in the watershed, except mixing (e.g. Sklash and Farvolden, 1979). The use of stable oxygen and deuterium as tracers in other hydrologic studies has provided greater insights into watershed water transport and stream generation (e.g. Sklash et al., 1986; Kleissen et al, 1990; Rose, 1996).

The spatial and temporal extent of rock-water interaction and the flow pathways of water within a watershed control the geochemistry of water. Chloride as a geochemical tracer is also conservative. Chloride concentration in water is controlled by additions by rock weathering or dilution along flow pathways within watersheds or by evaporative concentration. Reactive tracers that can be used to elucidate the sources of water in different hydrologic settings include the major ions and carbon isotopes. In principle, while solutes tracers only trace solutes, they also provide information on the types of reactions responsible for their presence in water (e.g. Sidle, 1998) and have been useful in providing qualitative and quantitative information on the flow pathways of precipitation in natural watersheds (Hooper et al., 1990; Kleissen et al., 1990; O'Brien and Hendershot, 1993; Elsenbeer and Lack, 1996; Chandeler and Bisogni, 1999).

Dissolved inorganic carbon (DIC), the isotopic ratio of DIC ($\delta^{13}C_{DIC}$) and radiocarbon (^{14}C) of DIC can be used to infer the source of water and trace water flow pathways in watersheds (Fritz et al., 1978; White and Chuma, 1987; Rose and Long, 1989; Chandeler and Bisogni, 1999). In a simplified conceptual model of high altitude watersheds, the concentration of DIC, $\delta^{13}C_{DIC}$ and radiocarbon of stream water is controlled primarily by it source (snowmelt or shallow groundwater discharge) and interaction with atmospheric CO_2. Water that flows underground is affected primarily by soil CO_2 and reactions with minerals in the soil zone and the aquifer. In addition, DIC reactions in organic rich sediments typical of meadows complexes are characteristic and distinguishable from stream water or groundwater in the underlying aquifer.

THE STUDY SITES

The wet meadow complexes selected for this study are located in the Big Creek watershed in the Toiyabe Range and Corral Canyon watershed in the Toquima Range in central Nevada (Fig. 1). The Big Creek and Corral Canyon watersheds occur within a physiographic province dominated by north-south oriented, fault-blocked ranges separated by intermontane basins. Big Creek and Corral Canyon were selected as typical wet meadow sites based on their geomorphology and vegetative composition (Chambers et al., 1999). Both sites are at similar elevation between 2100 and 2400 m and have been the subject of vegetative, hydrologic, stratigraphic and geomorphologic investigations (e.g. Chambers et al., 1999; 2000; Castelli et al., 2000; Jewett, 2000; Miller and Jewett, 2000; Martin and Chambers, 2001).

BIG CREEK

The meadow complex in Big Creek is located at elevation of 2146 m ($39^0$19'28"N, $117^0$7'16"W) in the Toiyabe Mountain Range (Castelli et al., 2000). The meadow complex occurs upstream of a valley constriction created by a side valley alluvial fan that extends almost across the entire width of the valley floor (Fig. 2). The site is about 300 m long and up to 75 m wide across the valley floor. There is approximately 25 m change in the valley floor elevation across the site (Miller and Jewett, 2000).

The geology of Big Creek watershed is primarily consolidated rocks and valley fill. The consolidated rocks include metamorphosed quartzites, quartz-mica schists, silicious slates, shales, dolomitic limestones and some conglomerates (Eakin et al., 1965). Detailed stratigraphy of the Big Creek meadow site has been described by Miller and Jewett, (2000). In general, the aquifer below the meadow complex is valley-fill consisting of unconsolidated sedimentary deposits ranging from highly permeable sands and gravels to low-permeability clay and silts interbedded with peaty material. The near surface material within the wet and mesic portions of the meadow complex consists of dense mat of roots and undecomposed organic material. Where alluvial fans dominate, the sediments grade from poorly sorted alluvial-fan deposits at the valley floor to well-sorted sand and gravel deposits next to the valley side.

Big Creek is the main stream that drains the watershed. Big Creek is a perennial stream and flows in a well developed channel. The channel at the study site ranges from

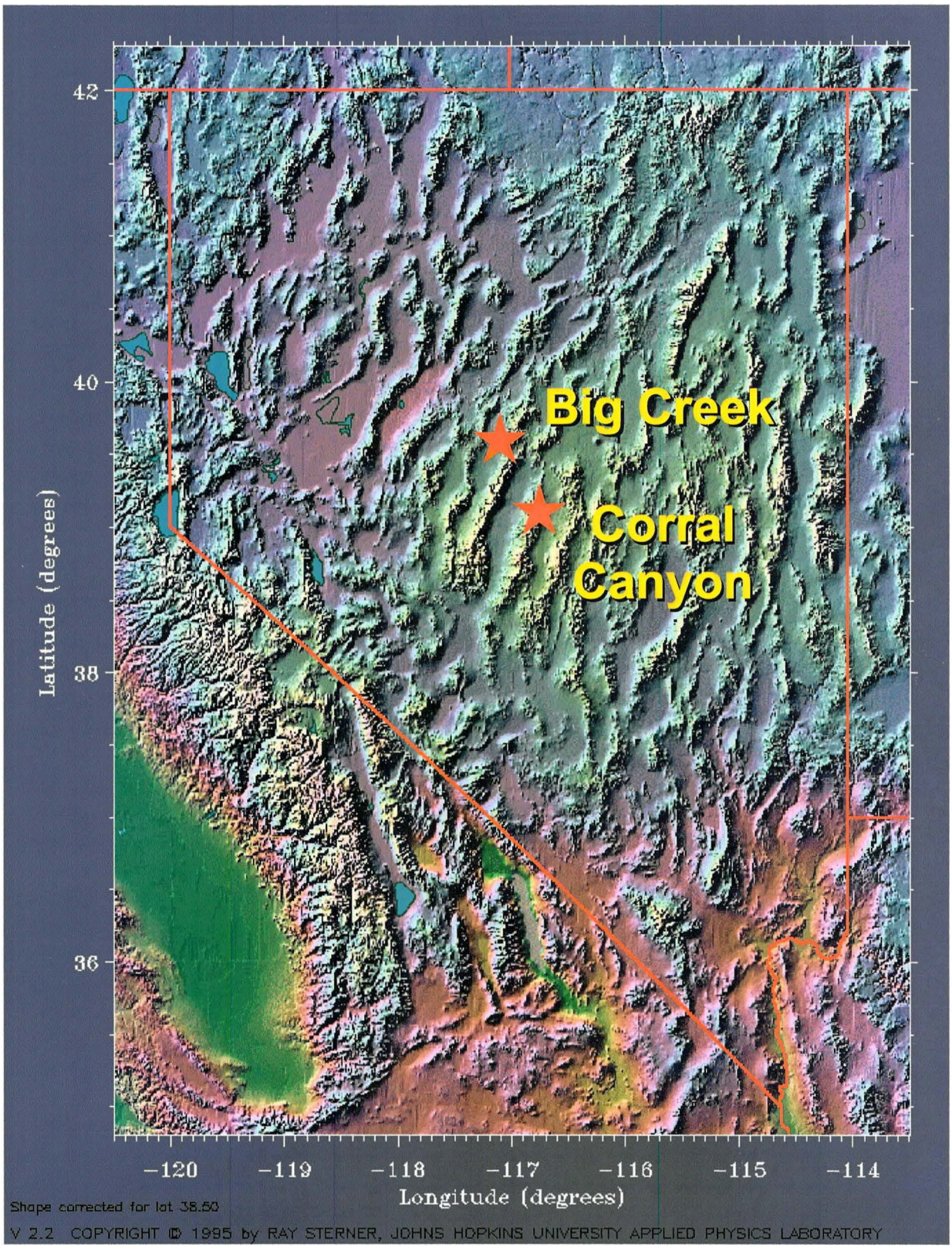

Figure 1. Locations of the Big Creek and Corral Canyon study sites in Nevada (Modified from Ray Sterner, 1995).

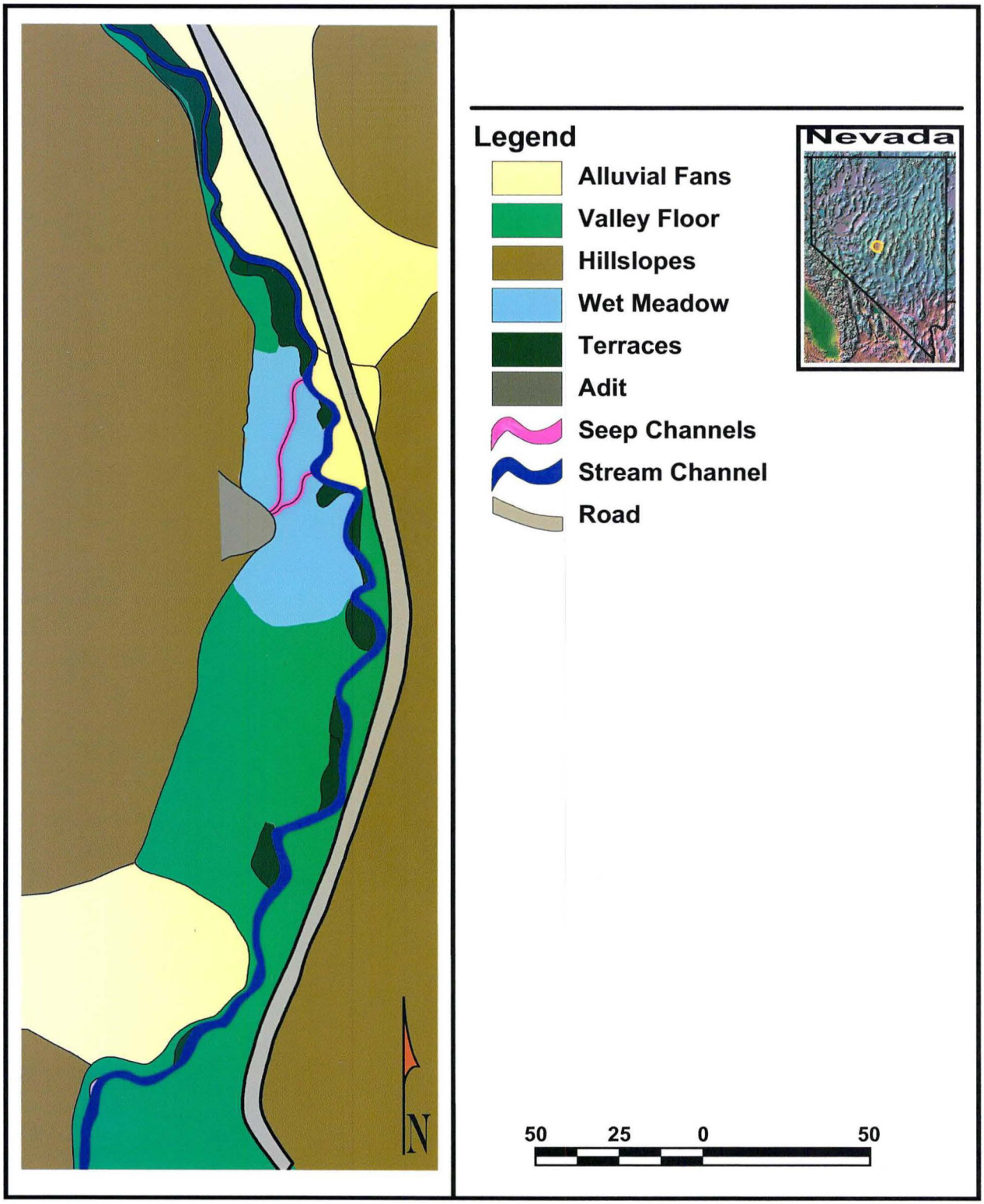

Figure 2. Map of Big Creek medow complex showing the geomorphic and hydrologic setting (Modified from Miller and Jewett, 2000).

about 1.5 to 6 m wide and is incised approximately 0.5 to 1 m below the valley floor (Miller and Jewett, 2000). There are several tributary streams which occur mainly above the study site. The source of water for the tributary streams appears to be snowmelt from higher elevations in addition to seeps and springs along valley sides. Several springs are apparent in the watershed where hydrophyllic vegetation has developed. At the Big Creek meadow complex, water issuing from an adit seep flows across the wet meadow portion in a poorly developed channel. Seepage of groundwater also occurs next to the stream adjacent to some birch trees (birch seep).

CORRAL CANYON

The Coral Canyon Meadow complex is located at elevation of 2377 m ($39^0$7'13.5"N, $116^0$48'38.66"W) in the Toquima Mountain Range (Castelli et al., 2000). The study location in the Corral Canyon watershed is approximately 4 km upstream of the confluence of Corral Canyon Creek with Stoneberger Creek (Fig. 3). The meadow complex is located upstream of a valley constriction created by a lower alluvial fan that extends into the valley and a bedrock protrusion (Miller and Jewett, 2000). The wet meadow complex is located within the center of the valley floor and is bound on the south by a bedrock outcrop and on the north by two side valley alluvial fans. The study area is approximately 900 m long and 200 m wide across the valley floor, with an approximately 20 m change in the valley floor elevation across the site (Miller and Jewett, 2000).

The geology of the watershed is primarily of Tertiary volcanic rocks, similar to those exposed in the Shoshone and Toiyabe Range (Eakin et al., 1965). The aquifer within the watershed consists of basin-fill deposits surrounded and underlain by volcanics (Thomas et. al., 1996). Rocks exposed near the meadow complex and in the headwater region of the watershed are welded and non welded silicic ash-flow tuff. Detailed stratigraphy of the study site has been described by Miller and Jewett, (2000). The upper 1 m consists of silts, fine sands and loam interbedded with peaty sediments. Below this interval, the material is mostly fine to medium sand, interbeddded with silt. At depths below 4 m, the material is predominantly coarse sand. Although the deposits are generally mixed, they probably grade from poorly sorted alluvial-fan deposits at the valley floor to well sorted sand and gravel deposits next to the valley sides.

Coral Canyon stream flows through the study area in a poorly developed channel about 30 cm wide and 20 cm deep. The stream channel is also poorly developed above the study site and no tributaries were observed at higher elevations in the watershed. There are several seeps within the study area. Especially prominent is seepage in the center of the study area where water issues from the ground and flows across the site into the stream. Several poorly developed channels carry water from seeps issuing from the meadow complex into the stream. Seeps and springs also develop in bedrock outcrops in the southeast portion of the site during periods of high groundwater, presumable as a result of recharge from snow melting. Seepage and springs also occur in the valley floor in other areas of the watershed.

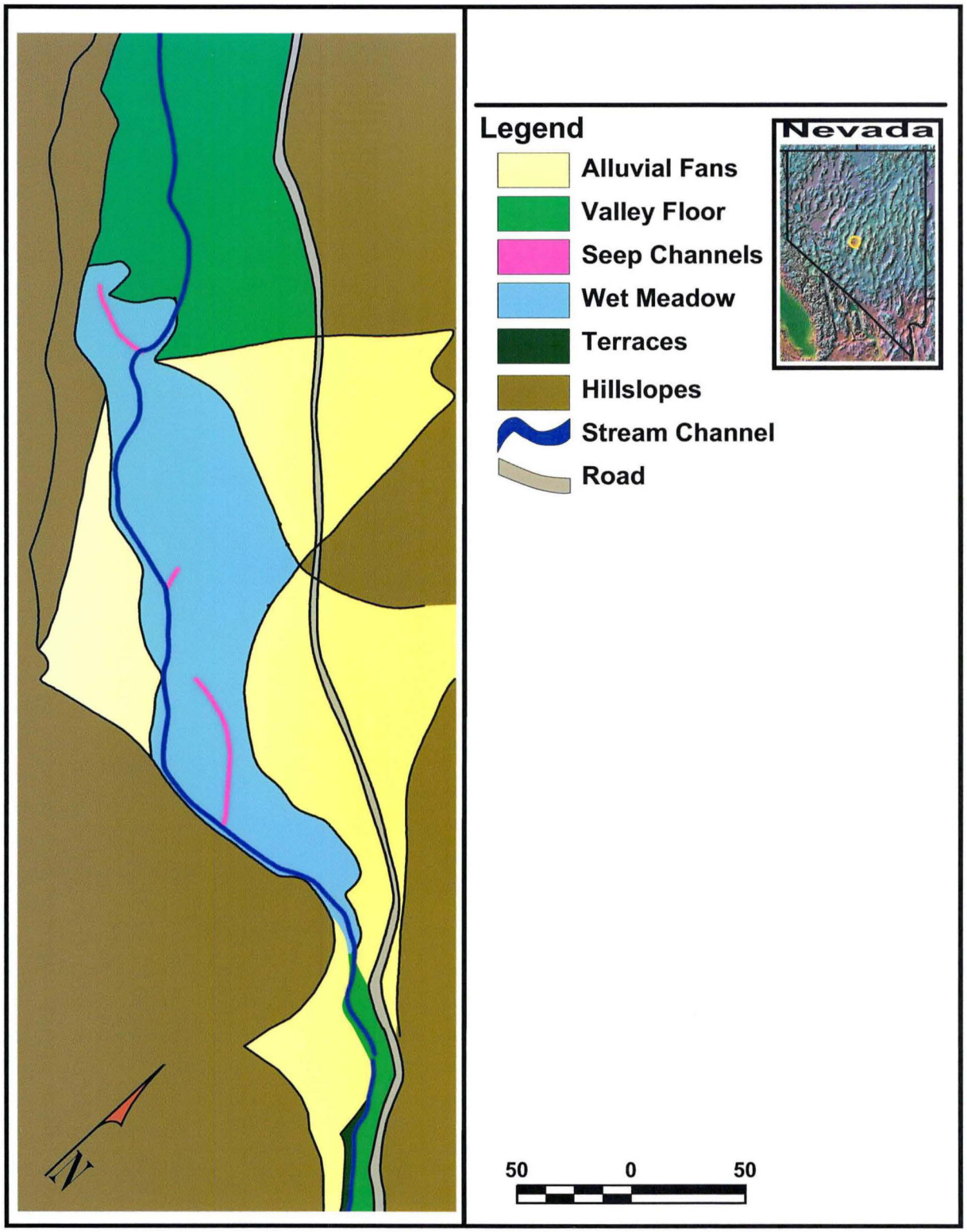

Figure 3. Map of Corral Canyon medow complex showing the geomorphic and hydrologic setting (Modified from Miller and Jewett., 2000).

METHODS

SAMPLING STRATEGY

In accordance with the objectives of this study, shallow groundwater and runoff from the meadow complexes and stream water adjacent to the meadow complexes were sampled to characterize the geochemical and isotopic composition. Additional water samples were collected from selected springs, seeps, and tributary streams to determine the geochemical and isotopic character of surface water and groundwater in the watersheds, and to provide a framework for understanding groundwater and surface water relation within each meadow complex. Water sampling for this study was conducted in November 1998, June 1999 and June 2000.

Big Creek

Sampling of Groundwater: Groundwater was collected from select locations from an existing network of monitoring wells and piezometers in the study area. For this study, monitoring wells were installed at strategic locations to augment the existing groundwater sampling network. The existing piezometers consisted of 1.9 cm thin-walled, electrical metallic tubes (EMT) (See Miller and Jewett, 2000 for installation technique). The newly installed monitoring wells were constructed from 5.2 cm PVC riser, fitted with PVC screens (20 slots per 2.54 cm). The screens were covered with standard well sock (geotextile) during installation to prevent fine sediments from clogging the screens. The monitoring wells were installed in hand-augured holes, and the annulus above the screen was sealed using bentonite to isolate the screened interval from shallower ground and surface water. Attempts to install monitoring wells manually in the dry meadow and alluvial fan were not successful due to the underlying substrate. Locations where groundwater was sampled for this study is shown in Figure 4, and the specifications for the piezometers and monitoring wells sampled are presented in Table 1.

Table 1. Piezometers and Monitoring Well Details for Big Creek Meadow Complex. (Modified from Miller and Jewett, 2000)

Well ID	Screened Interval (cm)	Depth (cm)	Stick-up (cm)	Relative Elevation (m)
PZ-7	100	630.1	72.5	22.81
PZ-51	100	522.8	57.0	20.92
MW-2	30	124.0	76.0	17.52
MW-26	50	71.0	65.8	14.77
MW-24	50	70.0	69.5	15.07
MW-24B	10	170.0	47.0	15.07
MW-24C	20	256.0	45.0	15.07
MW-3	30	180.0	91.3	12.03
MW-32	50	54.0	70.3	14.31
MW-4	50	159.0	60.0	12.68
MW-39B	10	70.0	59.0	11.31
MW-39C	17	160.0	55.0	11.31
MW-5	50	128.0	53.7	8.73

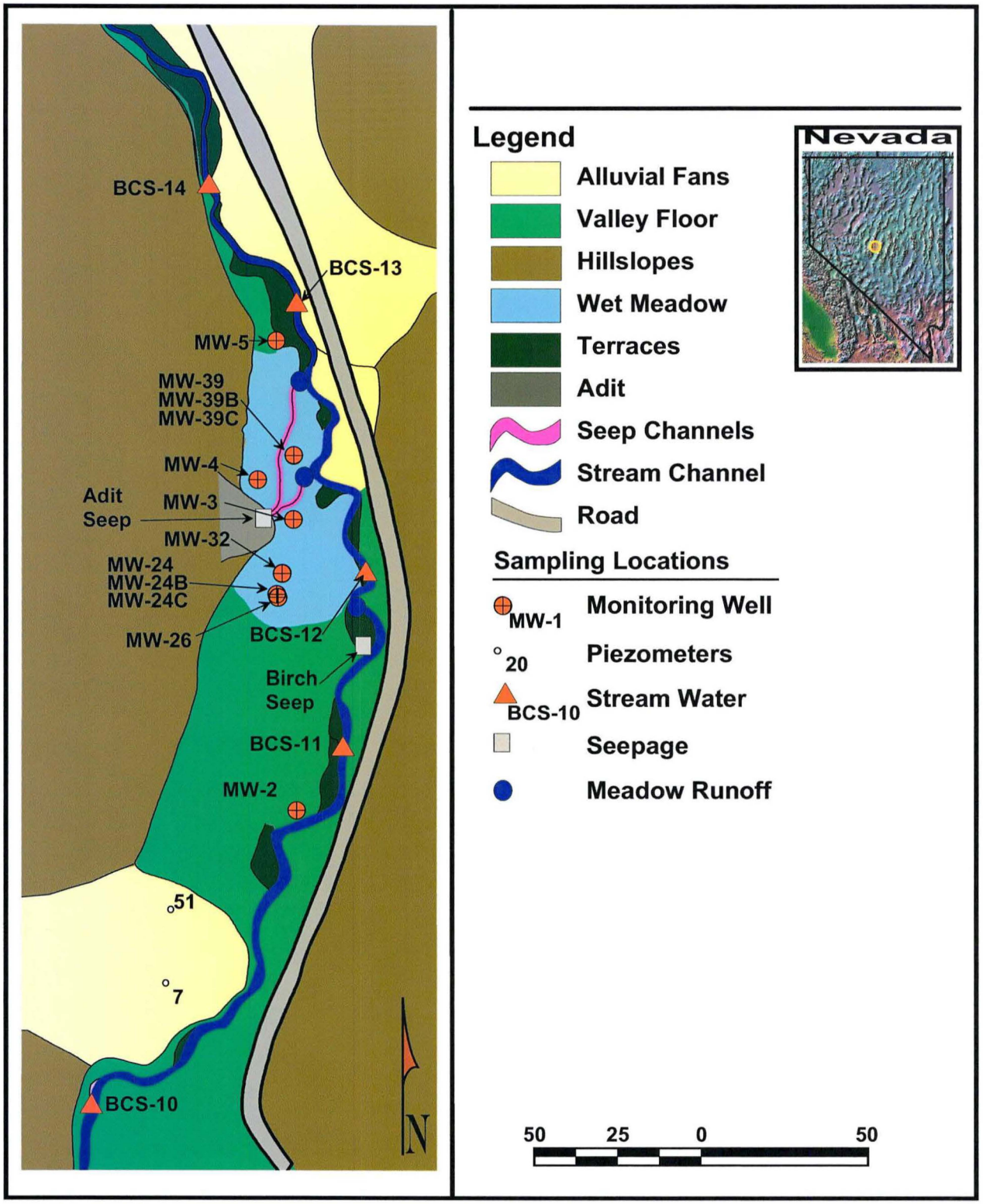

Figure 4. Map of the Big Creek meadow complex showing locations where ground and surface water were sampled (Modified from Miller and Jewett., 2000).

Groundwater was sampled from monitoring wells either by use of a Teflon® bailer or by pumping using a peristaltic pump. In sampling groundwater from monitoring wells using the bailer, at least three pore volume of water was removed from the well prior to sampling. In sampling groundwater using the peristaltic pump, water was pumped to the surface and the temperature, pH, and specific conductance were monitored. When these parameters were stable, the groundwater was sampled. Where monitoring wells and piezometers had low yield, the wells and piezometers were pumped dry three times and allowed to recover prior to sampling.

Sampling Seeps and Runoff from the Meadow Complex: Seeps were sampled from an adit seep and a seep next to Big Creek (Fig. 4). The seeps were sampled by the grab method at or near the source. It was sometimes necessary to create a small depression to allow sufficient water from seeps to collect prior to sampling. Runoff from the wet meadow portion of the site was sampled in July 1999 at two locations near their discharge point into Big Creek (Fig. 4).

Sampling of Stream Water: Stream water was collected from selected stream segments adjacent to the meadow complex at about 10 cm depths by the grab method. Five stream segments were selected for sampling which included a location above, three within and one below the study site (Fig. 4).

Additional Sampling within the Big Creek Watershed: Additional water sampled within the watershed included a spring, seeps, tributary streams, and select segments of Big Creek (Fig. 5). The spring and seeps were sampled at or near the source. The tributary streams were sampled near the confluence with Big Creek. Water was collected by the grab method as previously described.

Corral Canyon

Sampling of Groundwater: Groundwater was collected from select locations from an existing network of piezometers in the study area (Fig. 6). For this study, additional piezometers and monitoring wells were installed at strategic locations to augment the existing groundwater sampling network. Attempts to install additional piezometers and monitoring wells beyond the existing network within the sagebrush region (Castelli et al., 2000) and alluvial fans failed due to hard substrate and deeper depths to groundwater. Only the existing piezometer network was sampled during the study. The existing piezometers consisted of 1.9 cm thin-walled, electrical metallic tubes (EMT) (See Miller and Jewett, 2000 for installation technique). New monitoring wells were installed at three locations within the meadow complex. The construction and installation techniques are similar to that used in the Big Creek study area. Locations where groundwater was sampled for this study is shown in Figure 6, and the specifications for the piezometers and monitoring wells sampled are presented in Table 2.

Groundwater was sampled from monitoring wells either by use of a Teflon® bailer or by pumping using a peristaltic pump in a manner similar to the Big Creek study site.

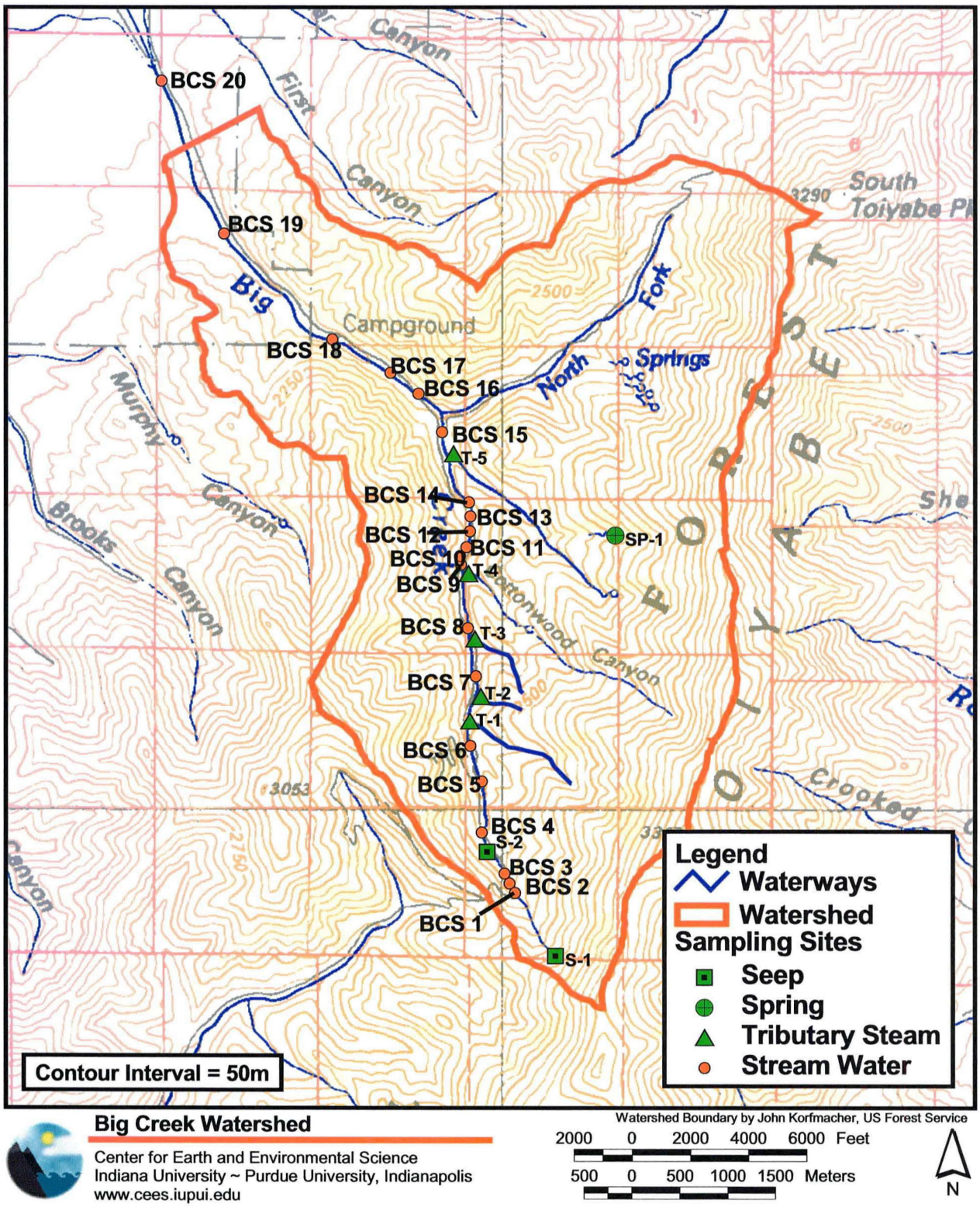

Figure 5. Topographic map of Big Creek watershed showing locations where stream water, seeps and a spring were sampled.

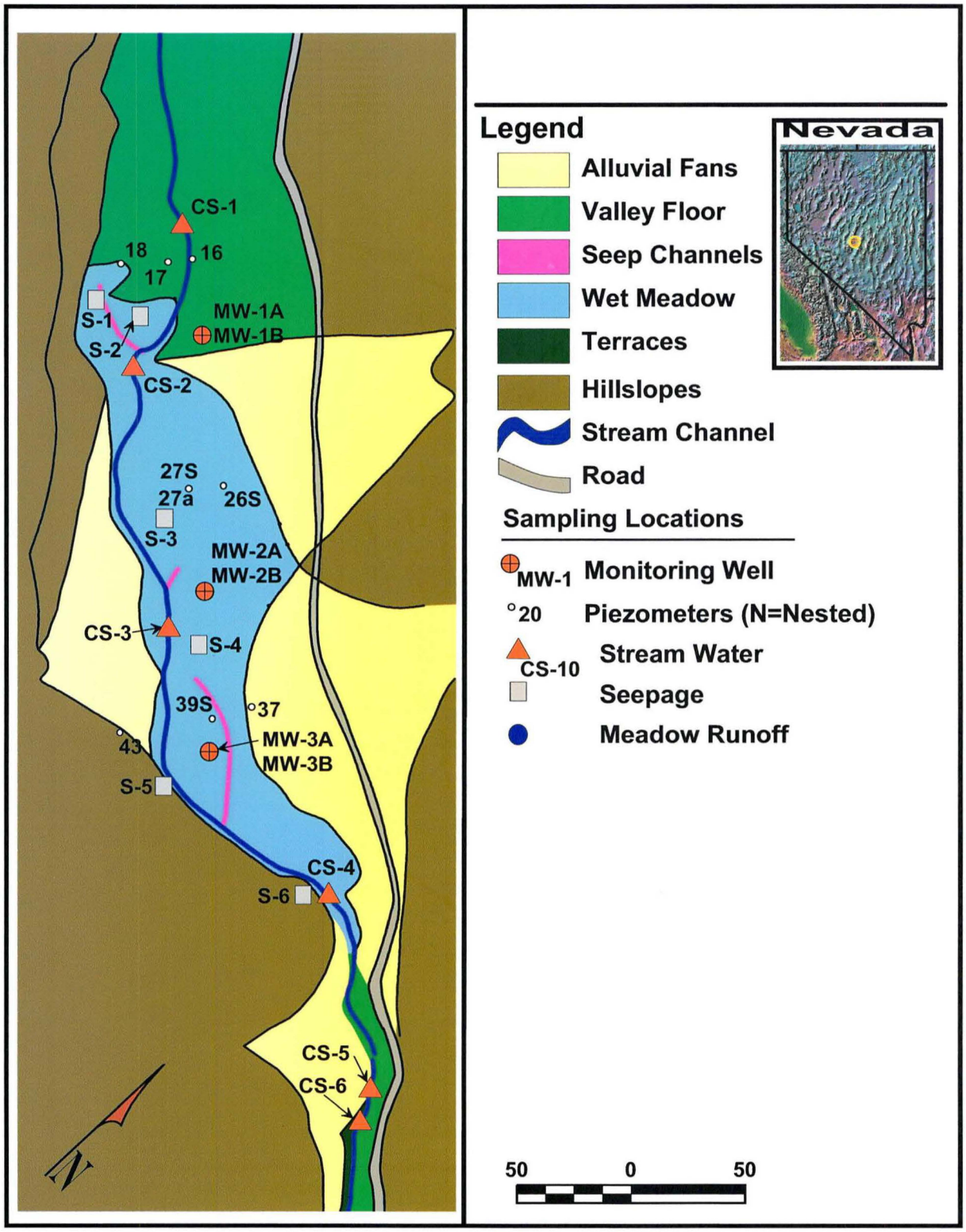

Figure 6. Map of the Corral Canyon study site showing locations where ground and surface water were sampled (Modified from Miller and Jewett., 2000).

Sampling Seeps and Runoff from the Meadow Complex: At the Coral Canyon meadow complex, four locations where seepage occurred were sampled. Additional seepage from the bedrock outcrop in the southern portion of the study area was also sampled. Runoff from the meadow portions of the site was sampled. Locations where seeps and meadow runoff were sampled are shown in Figure 6. Seeps and meadow runoff were sampled by the grab method similar to the Big Creek study site.

Stream Water: Five locations were selected for sampling Corral Canyon stream water at the study site. The segments selected included one above, three within and two below the meadow complex (Fig. 6). Stream water was collected from selected stream segments from the surface by the grab method previously described.

Table 2. Piezometers and Monitoring Well Details for Corral Canyon Meadow Complex. (Modified from Miller and Jewett, 2000)

Well ID	Screened Interval (cm)	Depth (cm)	Stick-up (cm)	Relative Elevation (m)
PZ-16	100	236.2	67.0	16.54
PZ-17	100	304.8	80.5	16.58
PZ-18	100	236.2	67.0	16.49
PZ-26	100	304.8	76.0	12.06
PZ-27	100	237.3	67.5	11.83
PZ-37	100	304.8	70.0	10.00
PZ-39	50	185.4	67.5	9.28
PZ-43	NA	NA	NA	NA
PZ-42	100	304.8	47.0	8.88
MW-1A	35	43.0	35.0	NA
MW-1B	10	255.0	55.0	NA
MW-2B	10	308.0	40.0	NA
MW-3A	10	121.0	59.0	NA

NA = Not available

Additional Water Sampling Within the Corral Canyon Watershed: Additional water sampled within the watershed included a spring and seeps in the valley bottom in the headwater region of the watershed. The spring and the seeps were sampled by the grab method previously described.

ANALYTICAL PROCEDURES

Field Analyses

Physical water parameters were measured in the field using a HydroLab™ downhole Minisonde. The probe of the Minisonde was lowered into stream water at selected stream segments, and at or near the source for springs and seeps. Water temperature, pH, and specific conductance were recorded after stabilization of the readings. For groundwater obtained from monitoring wells by bailers or monitoring wells with poor water yield, the physical parameters were measured in within the well

bore, after stabilization of the readings. For monitoring wells and piezometers sampled by pumping, the physical parameters were measured using a flow-through cell and readings were recorded after stabilization. In situations where it was not possible to obtain sufficient water from the wells and piezometers due to no recovery, no readings were taken. Alkalinity as bicarbonate was measured in the field for water sampled at each location by potentiometric titration using 1.5 N H_2SO_4 to an acid equivalent point of 4.5 (Hach, 1992).

Laboratory Analyses

Major Ions: Water analyzed for major ions were collected in a 250 ml HDPE bottles and cooled to 4°C on ice in the field. The samples were transported to the laboratory and filtered through a 0.45 μ filter. Samples analyzed for cations were acidified to a pH of 2 or lower. Major anion and cation analyses for water sampled in 1999 were carried out under the direction of Dr. Paul Lechler at the Nevada Bureau of Mines and Geology (NBMG). Anions were measured by ion chromatograph equipped with a conductivity detector and cations were measured by inductively coupled plasma-mass selective detector (ICP-MS). Water samples collected in 2000 were analyzed for major ions at the Department of Geology at Indiana University Purdue University Indianapolis (IUPUI) using a Dionex DX500™ Ion Chromatograph equipped with a conductivity detector.

Stable Isotopes: Water for oxygen isotopic analyses were collected and stored in leak proof 25 ml scintillation vials with inverted cone closures. In the laboratory, 2 ml of water was equilibrated with CO_2 at 25 ^{0}C (Socki et al. 1992). The equilibrated CO_2 was extracted under vacuum and analyzed for $\delta^{18}O$ by mass spectrometry.

Water for DIC and carbon isotopic analysis were collected and analyzed in the laboratory using a modification of the gas evolution extraction technique (Atekwana and Krishnamurthy, 1998). Briefly, 10 ml of water was collected from each sample location using a plastic syringe. The water in the syringe was injected into pre-evacuated septum tubes pre-loaded with 0.5 ml of 85% phosphoric acid and magnetic stir bars. The samples were transported to the laboratory where DIC was extracted from the septum tubes on a multi-purpose vacuum line. CO_2 yields were measured using a pressure transducer and used to determine DIC concentration. DIC concentrations are reported in mg C/l and have an overall precision of 1% (Atekwana and Krishnamurthy, 1998).

Isotope measurements of both $\delta^{18}O$ and $\delta^{13}C$ were made using an Isotope Ratio Mass Spectrometer at Western Michigan University, Kalamazoo, MI. The isotope ratios are reported in the δ notation where:

$$\delta\ (^0/_{00}) = ((R_{sample}/R_{standard}) - 1) \times 10^3$$

R is $^{18}O/^{16}O$ or $^{13}C/^{12}C$. The delta values are reported relative to the SMOW standard for oxygen and relative to PDB standard for carbon. Conversion to standard PDB carbon was made using NBS-19 standard. Routine $\delta^{18}O$ and $\delta^{13}C$ measurements have an overall precision of $0.1\ ^0/_{00}$.

Carbon-14: Water for carbon-14 analyses was collected and the CO_2 extracted in a manner similar to that for DIC analyses. The CO_2 was sealed in Pyrex tubes and shipped

to Purdue University Prime Lab, where Carbon-14 measurements were made using Accelerator Mass Spectrometry (AMS) technique. Carbon-14 values are reported in percent modern carbon (PMC).

RESULTS AND DISCUSSIONS

Determining the source of shallow groundwater in the meadow complexes using major ion chemistry and stable isotopes is based on the expected difference in chemical and isotopic evolution of stream and groundwater systems. Weathering reactions in soils and aquifers control chemistry of groundwater (e.g. Back, 1966; Freeze and Cherry, 1979; Hem, 1985; Dominico and Swartz, 1990; Wassenar et al., 1991). Stream water chemistry in the study areas is controlled by the ratio of direct snowmelt to groundwater discharge in stream discharge. Snowmelt is expected to contribute minimally to major ions and DIC in stream water. As stream discharge is augmented by groundwater contribution (base flow), stream chemistry is expected to change, but remain geochemically distinct from that of groundwater. Groundwater is generally characterized by higher concentrations of cations and anions compared to stream water. Thus, if the source of water supporting meadow complexes is stream water, the major ion chemistry should be similar to that of stream water or show evolutionary characteristics with stream water as an end member, except where it can be demonstrated that physical aspects of groundwater hydrology excludes this possibility. Alternatively, if the source of water supporting the meadow complexes is groundwater, the geochemistry of the shallow groundwater and meadow runoff should be different from stream water but similar to seeps and springs known to be of groundwater origin in the watershed.

BIG CREEK STUDY SITE

General Hydrochemistry

The results of analyses of shallow groundwater, runoff from the meadow complex, seepage and a spring from the Big Creek meadow complex and watershed are presented in Table 3. Although more than one sampling event was conducted at the study site, some sampling locations did not yield sufficient water for analyzing a complete suite of geochemical and isotopic parameters.

To investigate relationship between shallow groundwater and stream water from Big Creek, cation and anion proportions in water collected from the meadow study area and the watershed in 1999 and 2000 are shown on a trilinear diagram (Fig. 7). The trilinear diagram was constructed using the Rockware Scientific software and shows the relative concentrations of different ions in the water samples. Prior to constructing the trilinear diagram, the quality of major ion data was assessed by conducting an ionic charge balance. Two water samples from Big Creek stream and two samples of tributary streams flowing into Big Creek which had charge balance errors of 6% or more were excluded from this analysis.

In general, water from Big Creek watershed was dominated by the cations Ca and Mg, and anions HCO_3 and SO_4. The waters can be classified as Ca-HCO_3, Mg-HCO_3 or

Table 3. Chemical and Isotopic Analyses of Water from Big Creek Watershed.

	SAMPLE ID	Temp (C)	pH	SpC (µS)	NO_3 (mg/l)	Cl (mg/l)	SO^4 (mg/l)	HCO_3 (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	DIC (mg C/l)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	^{14}C (PMC)
November 1998																
Groundwater	PZ-51	-	-	-	-	-	-	-	-	-	-	-	23.8	-15.0	-16.3	-
	MW-24	4.0	7.06	657	-	-	-	-	-	-	-	-	103.2	-14.6	-16.1	-
	MW-32	1.9	7.36	574	-	-	-	-	-	-	-	-	122.3	-15.0	-15.7	-
	MW-3	1.5	7.17	496	-	-	-	-	-	-	-	-	74.8	-11.9	-16.3	-
	MW-4	4.5	7.31	623	-	-	-	-	-	-	-	-	77.8	-9.9	-16.0	-
Seep	Adit Seep	7.1	7.40	502	-	-	-	-	-	-	-	-	72.9	-10.7	-16.0	-
	Birch Seep	7.0	7.35	414	-	-	-	-	-	-	-	-	53.0	-10.7	-16.2	-
Runoff	Birch Seep	6.5	7.38	414	-	-	-	-	-	-	-	-	60.0	-10.3	-16.2	-
Stream Water	BCS10	5.2	8.00	341	-	-	-	-	-	-	-	-	39.9	-9.5	-16.1	-
	BCS11	5.5	7.97	342	-	-	-	-	-	-	-	-	43.6	-9.6	-15.8	-
	BCS12	5.1	8.09	363	-	-	-	-	-	-	-	-	42.5	-9.5	-16.3	-
	BCS13	4.7	7.95	381	-	-	-	-	-	-	-	-	40.7	-9.5	-16.1	-
	BCS14	4.5	7.07	383	-	-	-	-	-	-	-	-	39.3	-9.5	-16.3	-
July 1999																
Groundwater	PZ-7	-	-	-	-	-	-	-	-	-	-	-	53.0	-11.0	-16.3	-
	MW-24	9.9	7.87	540	<.02	2.5	49.6	311	14.9	1.8	65.2	35.8	57.6	-13.3	-16.6	99.6
	MW-24C	9.5	7.84	540	<.02	2.9	63.2	326	24.2	2.9	66.2	38.6	65.9	-12.0	-16.7	60.5
	MW 24-B	10.1	7.73	760	<.02	2.7	59.8	496	24.6	2.8	104.2	48.1	107.2	-15.6	-16.6	86.2
	MW-32	10.3	7.94	750	0.5	3.4	95.0	497	1.1	0.3	110.6	52.6	112.2	-14.4	-16.5	-
	MW-3	10.8	7.97	600	<.02	3.2	88.9	376	8.3	1.2	71.6	39.4	79.9	-13.4	-16.6	-
	MW-4	10.0	7.94	860	<.02	3.5	133.0	375	8.0	0.7	76.0	56.7	76.4	-9.8	-16.8	-
	MW 39-B	10.7	7.50	950	-	-	-	533	-	-	-	-	134.9	-13.6	-16.7	-
	MW-39-C	10.5	7.52	1100	5.5	4.7	175.0	583	7.4	1.1	145.2	72.7	151.2	-13.9	-16.8	99.6
	MW-5	10.4	7.76	640	-	-	-	-	-	-	-	-	85.0	-12.6	-16.4	
Seep	Adit Seep	10.2	8.36	590	<.02	3.2	85.5	317	0.2	0.9	60.2	40.8	59.3	-10.9	-16.5	49.1
	Birch Seep	10.5	8.17	460	0.4	3.4	66.0	290	8.6	0.7	57.6	35.3	56.1	-10.9	-16.6	-
Meadow Runoff	Runoff 1	16.8	8.69	600	<.02	3.5	62.6	296	23.6	1.6	59.8	35.2	53.5	-10.6	-16.7	-
	Runoff 2	11.4	8.74	630	0.2	3.5	62.6	329	1.0	0.2	68.0	48.4	61.8	-10.2	-16.5	-
Stream Water	BCS10	9.4	9.42	380	0.4	1.8	29.1	280	36.6	2.3	45.8	20.9	30.0	-9.3	-16.8	58.4
	BCS 12	12.2	9.22	390	0.4	1.9	34.2	283	26.6	1.7	42.8	20.2	34.6	-9.6	-16.8	58.4
	BCS 14	12.3	9.52	380	0.4	1.9	33.5	273	29.6	1.9	46.0	20.8	32.1	-9.3	-16.8	-
Watershed																
Spring	SP-1	8.6	8.15	970	<.02	9.0	202.0	441	50.1	2.5	85.6	77.1	85.1	-8.7	-16.5	35.0
Seep	S-2	6.1	8.14	380	0.6	1.2	39.3	271	16.5	0.5	37.0	27.8	38.9	-13.4	-17.0	-
Streamwater	BCS 1*	4.1	9.28	240	0.8	1.1	6.1	136	19.3	0.0	22.6	13.2	15.3	-9.6	-17.0	-
	BCS 6*	7.8	9.37	320	0.6	1.3	17.8	165	22.6	0.8	29.0	19.2	25.6	-9.8	-16.9	-
	BCS 8	9.2	9.46	350	1.2	1.6	26.7	180	11.7	0.3	29.4	20.8	27.6	-8.8	-17.0	-
	BCS 15	8.0	9.43	350	0.6	2.2	34.2	186	13.0	0.2	32.4	26.1	28.5	-8.2	-16.7	-
Tributary streams	TRIB-1	8.7	8.45	330	0.6	1.9	15.4	166	4.4	0.0	31.2	14.5	26.0	-8.5	-17.1	-
	TRIB-2	17.5	9.48	370	<.02	1.1	34.8	191	10.7	0.3	31.2	27.4	29.8	-8.0	-17.0	-
	TRIB-3	9.8	9.33	500	11.2	5.1	41.0	274	19.0	0.5	42.8	33.2	48.6	-10.0	-17.1	-
	TRIB-4*	8.2	9.61	300	0.8	1.4	21.2	143	13.3	0.1	29.6	15.3	22.9	-7.9	-17.1	-
	TRIB-5*	10.1	9.07	500	<.02	3.4	37.6	280	22.9	1.3	39.8	40.4	52.1	-10.7	-17.3	-
June 2000																-
Groundwater	MW-24B	12.5	7.41	424	<.02	1.8	63.7	368	7.7	1.7	78.5	46.8	67.3	-11.2	-16.4	-
	MW-24C	12.4	7.33	430	<.02	2.3	70.2	376	8.5	2.0	80.6	50.9	68.1	-10.7	-16.4	-
	MW-32	16.7	7.30	554	<.02	3.3	121.6	453	13.0	0.5	104.8	62.1	96.7	-11.9	-16.5	-
	MW-3	14.2			<.02	2.6	95.8	385	9.2	1.6	84.4	51.1	79.7	-11.7	-16.5	-
	MW-39B	12.7	7.29	571	<.02	2.8	117.9	448	9.6	0.9	113.3	59.7	89.9	-13.7	-15.9	-
	MW-39C	12.0	7.33	572	<.02	3.7	157.8	443	11.8	1.1	115.8	61.0	96.4	-13.5	-16.0	-
	MW-4	11.4	7.28	598	<.02	3.4	235.8	462	10.1	1.2	103.5	75.0	105.0	-10.1	-16.5	-
	MW-5	-	-	-	<.02	1.2	106.7	402	9.2	1.4	89.9	50.0	84.4	-12.8	-16.5	-
Seep	Birch Seep	9.5	7.30	425	<.02	2.1	80.3	322	8.2	1.3	75.3	46.1	57.3	-10.9	-16.6	-
Stream Water	BCS-1	11.6	7.50	193	<.02	0.5	10.4	196	2.9	0.6	40.4	19.6	36.2	-7.0	-16.7	-
	BCS-2	17.1	7.36	214	<.02	0.5	10.2	198	2.9	0.6	39.6	19.7	35.3	-8.0	-	-
	BCS-3	7.6	7.77	275	<.02	0.8	24.7	234	3.4	0.8	50.8	24.2	42.2	-10.9	-	-
	BCS-4	10.5	8.11	291	<.02	0.7	30.8	242	4.0	0.7	55.6	26.1	41.0	-10.6	-	-
	BCS-5	11.3	8.15	295	<.02	0.7	33.5	248	3.9	0.7	55.8	26.4	43.8	-10.4	-	-
	BCS-6	11.9	7.87	348	<.02	0.9	54.4	283	4.1	0.8	61.7	33.0	46.4	-10.3	-	-
	BCS-7	13.4	7.33	307	<.02	0.9	41.1	254	4.1	0.7	59.0	28.1	43.2	-7.5	-	-

Table 3. Continued

	SAMPLE ID	Temp (C)	pH	SpC (µS)	NO_3 (mg/l)	Cl (mg/l)	SO^4 (mg/l)	HCO_3 (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	DIC (mg C/l)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	^{14}C (PMC)
	BCS-8	11.5	7.42	337	<.02	1.0	48.2	266	4.3	1.1	61.8	29.7	47.1	-9.9	-	-
	BCS-9	12.8	7.32	348	<.02	1.1	53.8	264	4.7	1.1	64.7	32.6	48.7	-9.4	-	-
	BCS-10	12.5	7.35	356	<.02	1.3	56.2	273	5.1	1.1	65.4	32.9	48.5	-9.2	-16.7	-
	BCS-11	12.3	7.35	359	<.02	1.3	58.2	276	5.3	1.1	66.4	33.7	48.8	-9.3	-16.8	-
	BCS-12	11.2	7.43	363	<.02	1.4	58.9	283	5.5	1.2	68.6	34.7	49.4	-9.1	-16.8	-
	BCS-13	11.8	7.41	366	<.02	1.4	61.1	281	5.4	1.1	66.7	34.2	49.7	-9.1	-16.5	-
	BCS-14	12.5	7.34	361	<.02	1.4	59.5	288	5.7	1.2	69.8	35.6	48.2	-9.0	-16.7	-
	BCS-15	14.5	7.38	314	<.02	1.3	47.0	248	4.6	0.9	54.7	27.5	40.9	-7.8	-	-
	BCS-16	14.4	7.42	313	<.02	1.2	46.4	243	4.5	0.9	52.4	27.2	41.8	-7.4	-	-
	BCS-17	10.1	7.28	330	<.02	1.6	50.2	246	5.4	1.1	55.7	28.8	45.1	-8.9	-	-
	BCS-18	10.7	7.23	330	<.02	1.6	52.3	248	5.3	1.0	56.8	29.9	37.0	-8.9	-	-
	BCS-19	11.7	8.38	341	<.02	1.9	57.7	263	5.5	0.9	57.5	31.3	45.9	-7.9	-	-
	BCS-20	13.4	7.25	341	<.02	1.8	57.9	284	5.7	0.9	60.1	32.7	42.5	-8.2	-	-
Seepage	S-1	8.1	7.22	421	<.02	1.0	81.1	342	3.8	1.3	82.0	44.8	64.5	-11.7	-	-
	S-2	9.6	7.82	453	<.02	2.6	71.5	346	9.1	1.7	74.5	40.6	66.0	-9.1	-15.4	-

SpC = Specific conductance, - = not measured, * = ionic charge balance error greater than 6%

a mixed (Ca + Mg + Na) cation-HCO_3 type. Shallow groundwater in the meadow complex and seepage from the watershed showed characteristics of all three geochemical types. The spring sampled within the watershed was of a mixed cation-HCO_3 type. Stream water from Big Creek and tributary streams, were of the mixed cation-HCO_3, or Ca-HCO_3 type. All waters had similar proportion of SO_4, but differed in the proportion of HCO_3 by about 40 %. All water samples differ in the major cation proportion by about 30%. Several stream water samples were lower in Ca and Mg with respect to the other water samples, while some stream water showed cation proportions similar to those of groundwater within the meadow complex. In addition, some samples of seepage and the spring water known to have a groundwater source showed mixed cation-HCO_3-type water similar to some stream water samples.

There are no obvious mixing relations between shallow groundwater from the meadow complex and stream water that would suggest a similar geochemical source for these waters (Fig. 7). The cation-anion proportions shown in the trilinear diagram suggests that there may be more than one geochemical source of water supplying shallow groundwater in meadow complex. Alternatively, the difference in the geochemistry between shallow groundwater and stream water may suggest different chemical evolution of groundwater within the meadow complex. Although the major ion chemistry support different geochemical evolutionary pathway for water within the watershed, such geochemical differences could also result from import of water into the basin through major faults.

Source of Water in Big Creek Watershed

Stable oxygen isotopes can provide insights into the source of water within the watershed and the source of water that support vegetation in the meadow complex. The utility of stable oxygen isotopes for determining water sources is based on the principle that temporal variations in recharge of stream and groundwater should be distinguishable, since the mechanism of flow and the residence of water derived from snowmelt and water

flow through surface and groundwater systems are different (e.g., Buttle et al., 1995, Sidel, 1998). In addition, stream water is generally of local origin (within the watershed) while contributions to groundwater could come from interbasin flow through fracture, faults or regional groundwater flow. Out-of-basin source of water is expected to have an isotopic signature different from the local precipitation.

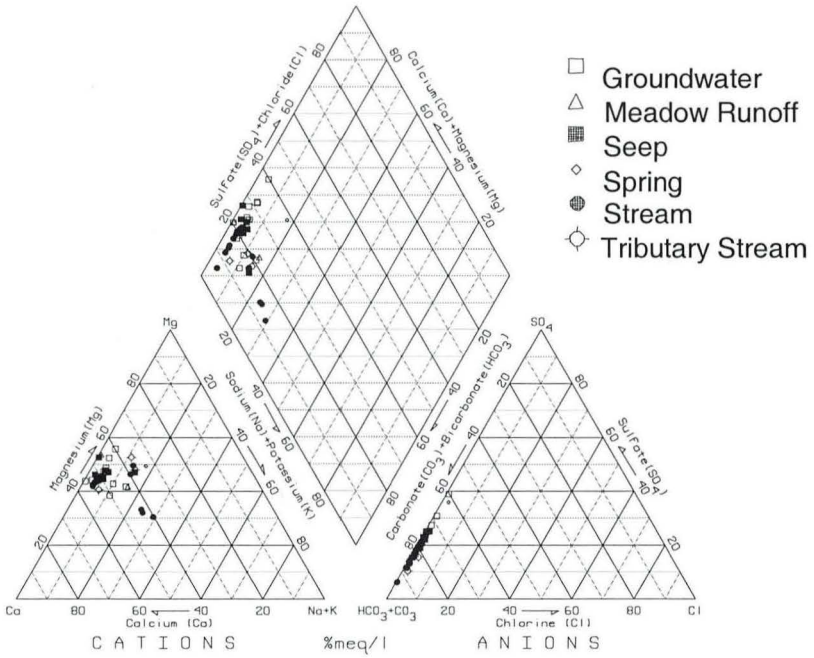

Figure 7. Chemical Composition of Water from the Big Creek Watershed.

Stable oxygen isotopes ($\delta^{18}O$) for 55 water samples collected in November, 1998, July, 1999 and June 2000, ranged from –17.3 to –15.7 $^{0}/_{00}$, with a mean of -16.5 $\pm$ 0.4$^{0}/_{00}$ (Table 3). The $\delta^{18}O$ values of these samples which include stream water, shallow groundwater, seeps and a spring were similar to values reported for this part of the Great Basin (Davisson et al., 1999). The $\delta^{18}O$ value of spring water and mean $\delta^{18}O$ values for seeps, shallow groundwater and runoff from the meadow complex, Big Creek stream water and tributary streams are shown in Figure 8. The mean $\delta^{18}O$ values for tributary streams are statistically different and are lighter than Big Creek stream water, seeps, spring, and shallow groundwater at the meadow complex. Although the isotopic dynamics of snow melting was not studied, tributary streams were only sampled in July 1999, during a period when significant stream flow occurred in the tributaries. The fact that these same tributaries had little or no flow in June 2000, suggest that their discharge was directly influence by snow pack volume. The differences in the $\delta^{18}O$ values of tributary stream may simple reflect the fact that Big Creek stream and groundwater represent the averaged seasonal $\delta^{18}O$ values of precipitation. The lack of significant differences between the mean $\delta^{18}O$ values of Big Creek stream water, shallow groundwater and runoff from the meadow complex, seeps, and the spring suggest that water within the watershed was derived from local precipitation. The deviations around the mean could be due to temporal recharge relative to melting of snowmelt or differences in the residence time in the different water reservoirs in the watershed. In

addition, the $\delta^{18}O$ data suggest no significant inter-basin groundwater transport occurring, since out of basin groundwater such as springs and seeps had similar $\delta^{18}O$ values to stream water generated locally from snowmelt.

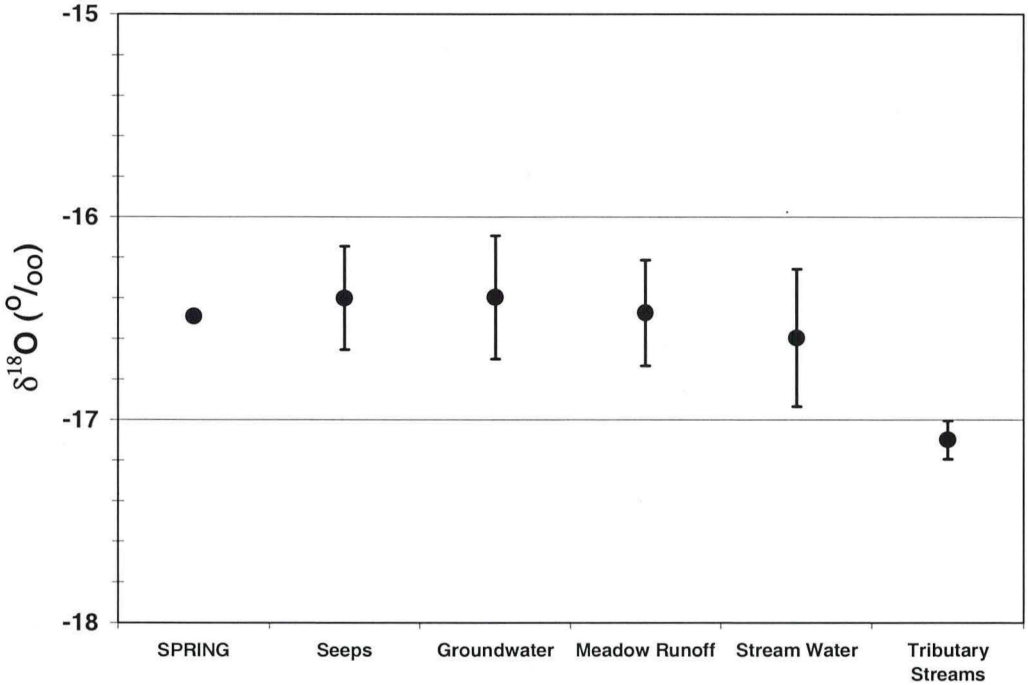

Figure 8. $\delta^{18}O$ in Selected Water Samples from the Big Creek Watershed.

Chemical and Isotopic Evolution of Water in Big Creek Watershed

The chemical and isotopic evolution of groundwater resulting from mineral weathering is predictable based on the rock and soil mineralogy and the interaction with soil CO_2. For carbonate aquifers systems, weathering reactions responsible for the major ion chemistry, DIC and $\delta^{13}C_{DIC}$ is controlled by soil CO_2. Thus coupling major ions, DIC and $\delta^{13}C_{DIC}$ can provide additional insights into local vs. watershed scale groundwater geochemical evolution. In addition, such analyses can also provide information on the geochemical origin of local sources of water that maintain riparian meadow complexes.

On a watershed scale, the geochemical and stable carbon isotopic evolution is compared with the shallow groundwater from the meadow complex. In this analysis, only water sampled in June 2000 was used, since during this sampling event, spatial sampling of Big Creek stream water was accomplished. Distances of Big Creek sampling stations were measured along flow direction, starting from the uppermost road stream crossing in the headwater of the watershed (Fig. 5). Stream water sampled from Big Creek near the study site was sampled between stations BCS 9 through BCS 14. The average value for various parameters for shallow groundwater from the meadow complex was plotted at 3.9 km, corresponding to distance of the meadow complex along the stream profile of Big Creek.

The spatial distribution of water quality parameters pH, temperature, and specific conductance from Big Creek stream water along with mean values for similar parameters

for shallow groundwater from the meadow complex is shown in Figure 9. Significant variation in the pH of stream water occurred mainly in the upper reaches of the watershed

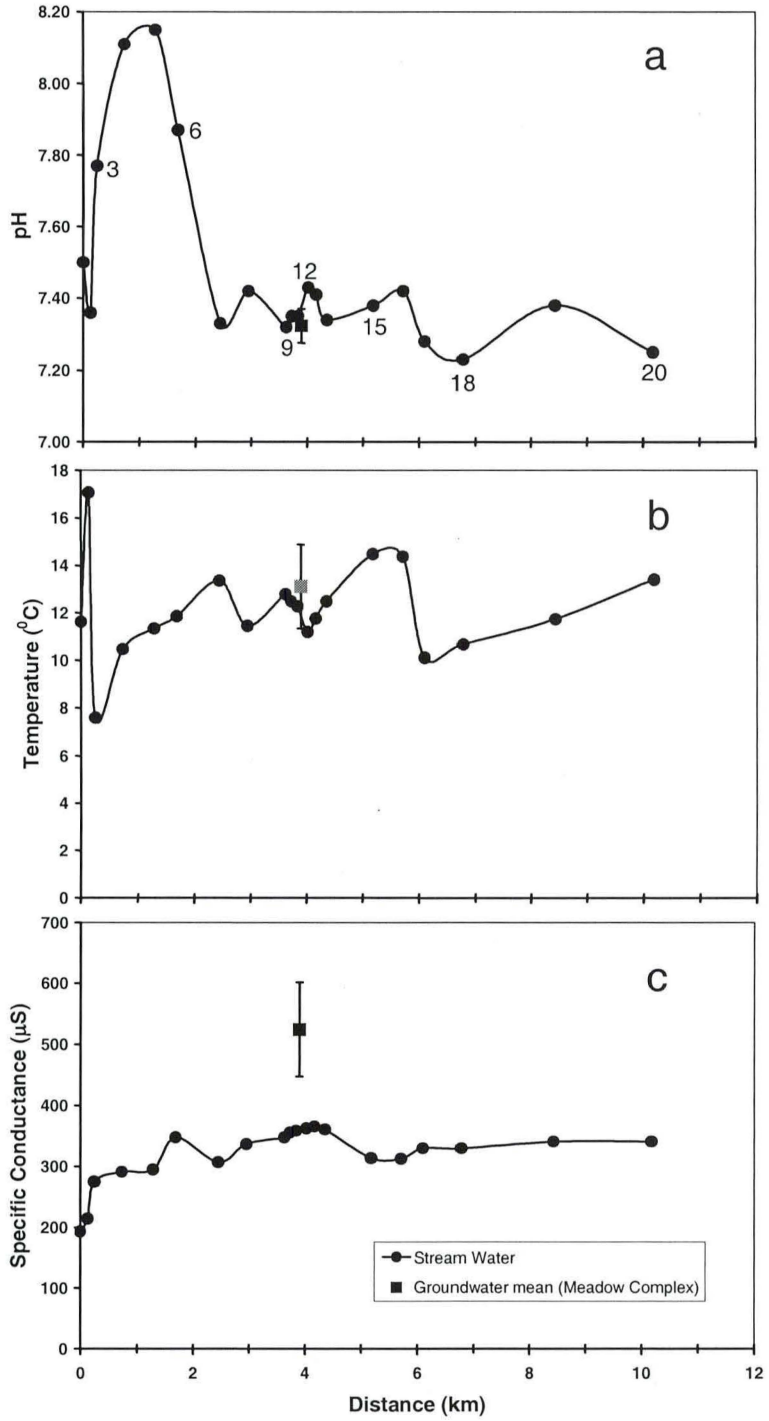

Figure 9. Spatial Distribution of ph, Temperature and Specific Conductance in Big Creek Stream Water Relative to the Mean Values for Similar Parameters in Shallow Groundwater from the Big Creek Meadow Complex. Every Third Station Number for Big Creek is shown in the Upper (a) Figure.

(BCS 1 through BCS 6) compared to the pH of stream water in the lower portions of the watershed (Fig. 9a). The mean groundwater pH from the meadow complex was similar to that of stream water adjacent to the meadow complex (BCS 9, 10, 11 and 14) and different from the downstream stations (BCS 12 and 13). It is not clear if the pH is diagnostic of any possible relationship between groundwater and stream water at the meadow complex.

The spatial distribution of temperature is shown in Figure 9b. It is observed that shortly downstream of the headwater region, temperature generally increased except for significant decreases at stations BCS 8, 12 and 17. The decrease in temperature suggests colder water from groundwater recharge at or in the near upstream regions of these stations. Groundwater mean temperature from the meadow complex was similar to stream water adjacent to the site, and may be responsible for depressing stream water temperature through groundwater discharge.

The specific conductance along Big Creek is shown in Figure 9c. The specific conductance increased dramatically between the headwaters and station BCS 3. Between station BCS 3 and 14, the specific conductance increased gradually except for station BCS 6. At station BCS 15, the specific conductance dropped and remained nearly constant to the mouth of the basin. The increase at BCS 6 may be the result of input of groundwater with high specific conductance, while the decrease observed at BCS 15 may have resulted from tributary input downstream of the meadow complex. It is also important to note that the specific conductance of groundwater from the meadow complex was significantly higher compared to stream water adjacent to the site. In addition, the stream water adjacent to the meadow complex showed a slight increase in the downstream direction suggesting possible input of groundwater into the stream segment at this location.

The spatial distribution of major anions chloride, sulfate and bicarbonate from Big Creek along with the mean values for similar parameters for shallow groundwater from the meadow complex is shown in Figure 10. Spatial trends for stream water for all anions showed a dramatic increase from the headwaters to BCS 3, a more gradual increase to BCS 14 (except for BCS 6), a drop at BCS 15 and a gradual increase to the mouth of the watershed. The dramatic increase in chloride, sulfate and bicarbonate between the headwaters and BCS 3 and at BCS 6 was probably due to significant augmentation of base flow in these stream segments, while the decrease associated with BCS 15 may be due to tributary influx into Big Creek downstream of the meadow complex. For all the major anions, the mean values for shallow groundwater from the meadow complex were higher than that for stream water sampled adjacent to the meadow complex. Also, the values of chloride, sulfate and bicarbonate increased systematically in the downstream direction across the meadow complex, suggesting that the increase may be due to local augmentation of stream flow by groundwater from the meadow complex.

The spatial distribution of potassium, sodium, magnesium and calcium for Big Creek stream water along with the mean values for similar parameters of shallow groundwater from the meadow complex is shown in Figure 11. Potassium, sodium, magnesium and calcium values for Big Creek showed dramatic increases from the headwaters to BCS 3 and gradually increased (except BCS 6) to BCS 14 , decreased at BCS 15 and gradually increased to the mouth of the watershed. This spatial trend is

similar to that of the major anions. Potassium generally showed only small changes in the direction of stream flow compared with other major cations (Fig. 11a vs. 11b, 11c and 11d).

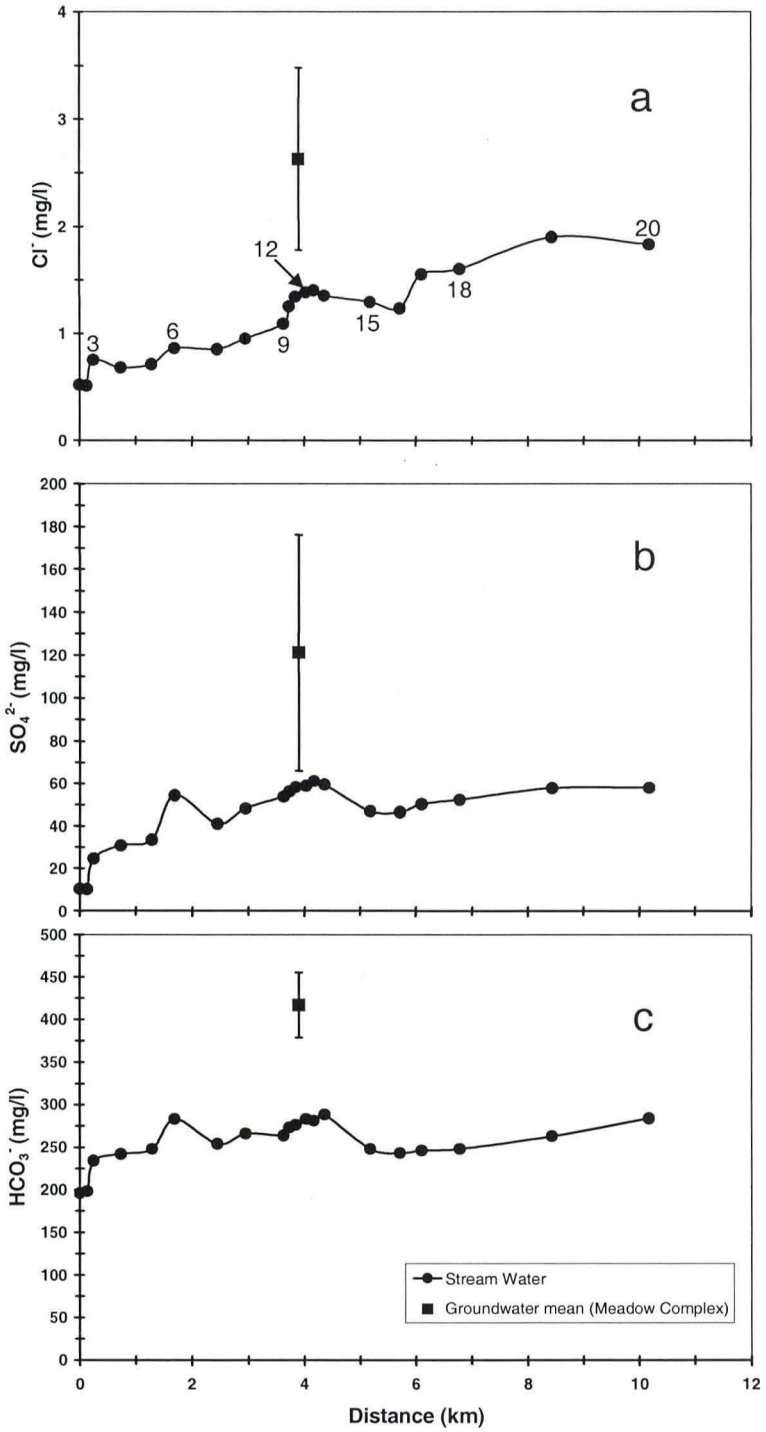

Figure10. Spatial Distribution of Cl, SO_4, HCO_3 in Big Creek Stream Water Relative to the Mean Values for Similar Parameters in Shallow Groundwater from the Big Creek Meadow Complex. Every Third Station Number for Big Creek is shown in the Upper (a) Figure.

Amongst the cations from shallow groundwater from the meadow complex, only potassium had values that were similar to Big Creek stream water adjacent to the meadow complex (Fig. 11a). Again, besides BCS 6, significant increases in major cations along

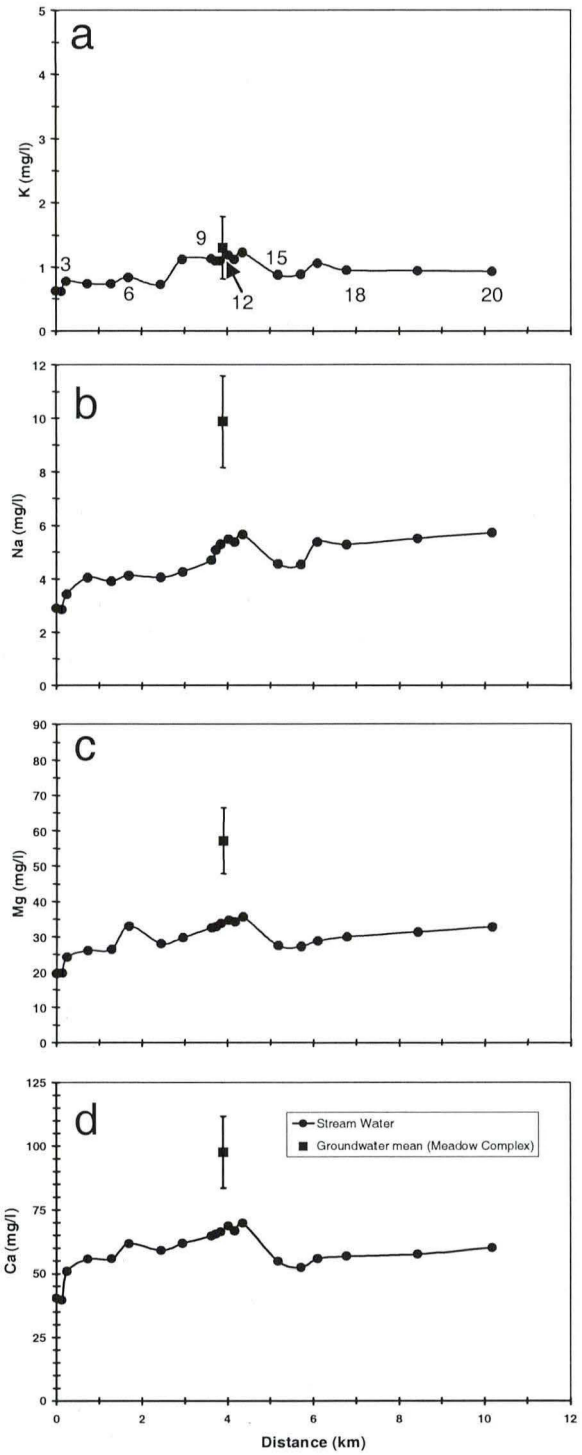

Figure 11. Spatial distribution of K, Na, Mg, and Ca in Big Creek Stream Water Relative to the Mean Values for Similar Parameters in Shallow Groundwater from the Big Creek Meadow Complex. Every Third Station Number for Big Creek is shown in the Upper (a) Figure.

stream segments adjacent to the meadow complex suggest that shallow groundwater from the meadow complex may be responsible for such increases (Figs. 11 b, c, and d).

The spatial distribution of DIC and $\delta^{13}C_{DIC}$ for Big Creek stream water along with the mean values for similar parameters from shallow groundwater from the meadow complex is shown in Figure 12. Changes in DIC were similar to anions and cations, increasing dramatically from the headwaters to BCS 3, increasing gradually to BCS 14, decreasing at BCS 15 and remained nearly constant to the mouth of the basin (Fig. 12a).

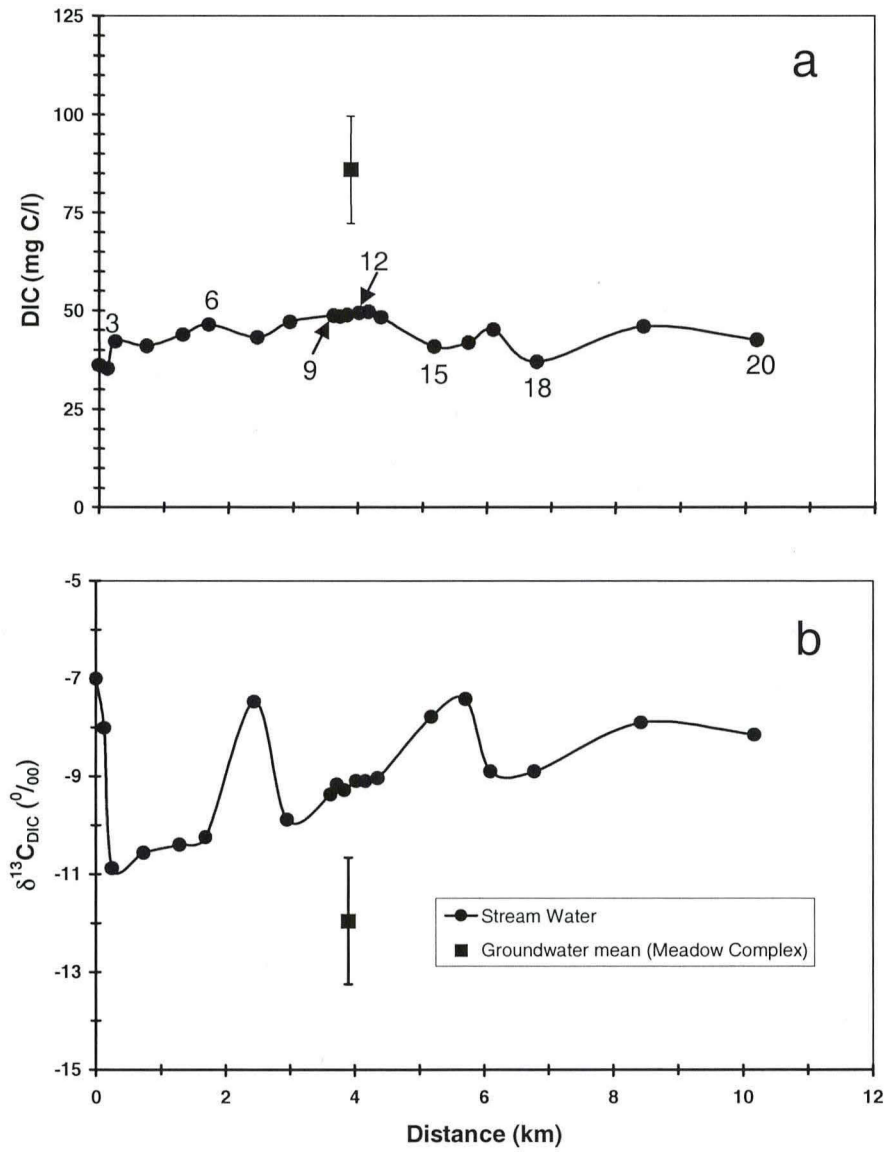

Figure 12. Spatial distribution of DIC and $\delta^{13}C_{DIC}$ in Big Creek Stream Water Relative to the Mean Values for Similar Parameters in Shallow Groundwater from the Big Creek Meadow Complex. Every Third Station Number for Big Creek is shown in the Upper (a) Figure.

The mean DIC for shallow groundwater from the meadow complex was higher than for stream water. The DIC for stream water from segments of Big Creek adjacent to the meadow complex increased in the downstream direction, although only slightly. The

slight increase may suggest local shallow ground water input of additional DIC into the stream system, and is consistent with the major ion data.

The $\delta^{13}C_{DIC}$ drastically decreased from the headwaters to BCS 3 and increased systematically to BCS 16, except for a dramatic increase associated with BCS 7 (Fig. 12b). The $\delta^{13}C_{DIC}$ decreased at BCS 17 and increased slightly towards the mouth of the watershed. The $\delta^{13}C_{DIC}$ data suggest that in the headwater region where most of the water was derived from melting of snow, the DIC is controlled by interaction with heavy carbon. The source of this heavy carbon is probably heavy CO_2 in the soil zone. In desert and semi-arid environments, the oxidation of C-4 in the soil zone will produce heavy DIC (Clark and Fritz, 1997; White and Chuma, 1987). The initial decrease at BCS 3 may be indicative of contributions to the DIC from C-3 vegetation within the valley floor (Clark and Fritz, 1997, White and Chuma, 1987). The plot also shows that as recharge stream water by groundwater occurred, the $\delta^{13}C_{DIC}$ decreased. The systematic increase of $\delta^{13}C_{DIC}$ to BCS 16 suggest, lateral recharge from the valley slopes dominated by C-4 vegetation. Alternatively, the increase in the $\delta^{13}C_{DIC}$ could result from interaction with the atmospheric CO_2. Possible side valley recharge of stream water with heavy $\delta^{13}C_{DIC}$ is supported by the much heavier $\delta^{13}C_{DIC}$ at BCS 7, where Big Creek was augmented by the first major tributary with a source of water from higher elevation with possible C-4 vegetation. Interestingly, the mean $\delta^{13}C_{DIC}$ of shallow groundwater from the meadow complex was much lower than for stream segments sampled adjacent to the meadow complex, even though the $\delta^{13}C_{DIC}$ increased slightly in a downstream direction across the meadow site.

The major ionic data suggest input of shallow groundwater along the meadow complex into the stream. However, the $\delta^{13}C_{DIC}$ provide additional evidence that this water may not interact significantly with carbon in the meadow complex. This is hydrologically possible if the meadow complex represents a groundwater discharge zone, such that only the upper shallow groundwater interacts with carbon in the meadow complex. The bulk of the groundwater discharged into the stream segment around the meadow complex was of a slightly deeper source which did not interact with meadow carbon.

To further explore the relationship between watershed stream water chemical and isotopic evolution relative to shallow groundwater within the meadow complex, chloride, a conservative tracer was plotted against $\delta^{13}C_{DIC}$ (Fig. 13). A regression model was applied to stream water. Excluded from the regression model were stream water samples from BCS 1, 2, 7, 15, and 16. Stream water from these segments of Big Creek had unusually high $\delta^{13}C_{DIC}$. The spatial ionic and isotopic data suggested that BSC 1 and 2 may be influenced from shallow recharge from snowmelt that has not undergone significant geochemical evolution and influence by heavy $\delta^{13}C_{DIC}$. Water from BCS 7, 15 and 16 were also influenced by tributary discharge, supplying water to Big Creek with heavy $\delta^{13}C_{DIC}$. With these stream samples eliminated, the fit of the linear regression model to the stream water chloride and $\delta^{13}C_{DIC}$ is significant (R^2 = 0.95) at 95% confidence. The model suggests proportional mixing of stream water with low chloride and light $\delta^{13}C_{DIC}$ in the upper watershed with water of higher chloride and heavier $\delta^{13}C_{DIC}$ in the downstream direction. An alternative explanation for such a trend in the stream water chloride-$\delta^{13}C_{DIC}$ model could be evaporative enrichment (Gremillion and

Wenielista, 2000). Evaporative enrichment will increase the chloride content of the stream water. The process responsible for evaporative enrichment (interaction with the

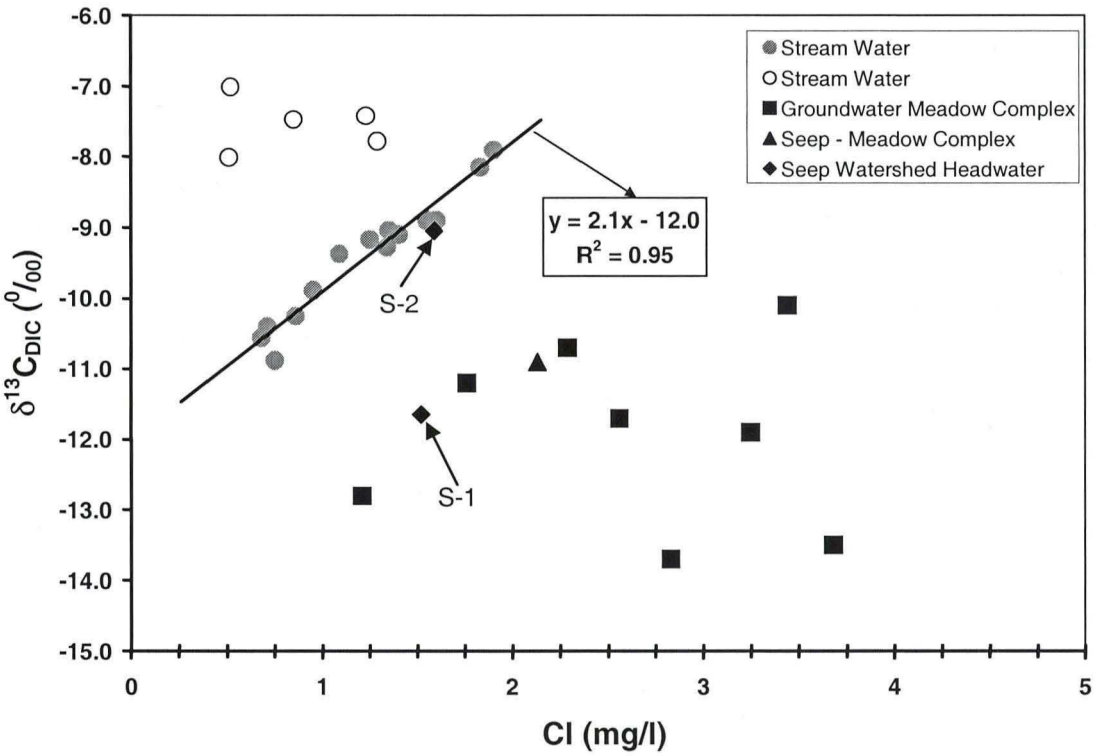

Figure 13. Cl vs. $\delta^{13}C_{DIC}$ for stream Water, Seepage and Shallow Groundwater from the Big Creek meadow Complex in the Big Creek watershed.

atmosphere) will also result in the preferential transfer of ^{12}C relative to ^{13}C to the atmosphere, resulting in an enrichment of the $\delta^{13}C_{DIC}$ (Clark and Fritz, 1997). The evaporative enrichment hypothesis is not consistent with observed the slight increase in DIC in Big Creek in the downstream direction. It is expected that preferential loss of 12C to the atmosphere will significantly reduce the stream water DIC in the downstream direction.

Also plotted in Figure 13 is seepage collected in the headwater region (S-1 and S-2) and seepage and shallow groundwater from the Big Creek meadow complex. Shallow groundwater from the Big Creek meadow complex shows no genetic relationship to stream water suggesting a different geochemical and isotopic evolution of shallow groundwater in the meadow complex. The only water sample with a likely groundwater origin that plots close to the regression model line is a side valley seep (S-2), which was collected near Big Creek and upgradient from BCS 4 (Figure 5). Side valley seeps have been reported for this watershed (Miller and Jewett, 2000). Evidence of significant groundwater flow along side valley occurs as seeps near the valley floor. The Cl-$\delta^{13}C_{DIC}$ suggests that side valley groundwater flow with heavy carbon may represent an important source of stream water in this watershed.

Chemical and Isotopic Evolution of Water in Big Creek Meadow Complex

The stable isotopic oxygen data for Big Creek watershed suggested locally derived water from snowmelt as the source of water within the watershed. The watershed scale geochemical and stable carbon isotopic analyses suggest that shallow groundwater in the meadow complex is not genetically related to stream water (Fig. 13). These interpretations do not exclude the possibility of stream water influx into the meadow complex as a source of water to support meadow vegetation. To investigate this possibility, a combined assessment of major cations and $\delta^{13}C_{DIC}$ was conducted.

The major cations produced during weathering reactions in the Big Creek watershed are calcium and magnesium (Fig. 7). Since chemical reactions between water and minerals are initiated and sustained by CO_2 within the soil zone and in the aquifer, changes in the calcium and magnesium or their ratio relative to CO_2 (DIC) and the carbon isotopic ratio of DIC can be predicted. The final $\delta^{13}C_{DIC}$ for isotopically evolved groundwater with CO_2 from C-3 vegetation (-23$^0/_{00}$) is about -14.0$^0/_{00}$ or -11.5 $^0/_{00}$ for open or closed system dissolution of carbonates, respectively (Clark and Fritz, 1997, Cane and Clark, 1998). If C-3 vegetation (-13 $^0/_{00}$) is involved in this process, the final $\delta^{13}C_{DIC}$ for isotopically evolved groundwater is about -6.5$^0/_{00}$ or -4.0 $^0/_{00}$ for open or closed system dissolution of carbonates, respectively (Clark and Fritz, 1997, Cane and Clark, 1998). Thus during the weathering reaction, the rate of change of the CO_2 or DIC will be related to the production of calcium and/or magnesium in the groundwater and the $\delta^{13}C_{DIC}$ will be related to the vegetation of the source CO_2.

To understand the local evolution of groundwater in the meadow complex, $\delta^{13}C_{DIC}$ was plotted against Ca/Mg (Fig. 14). Included in the plot are samples of runoff

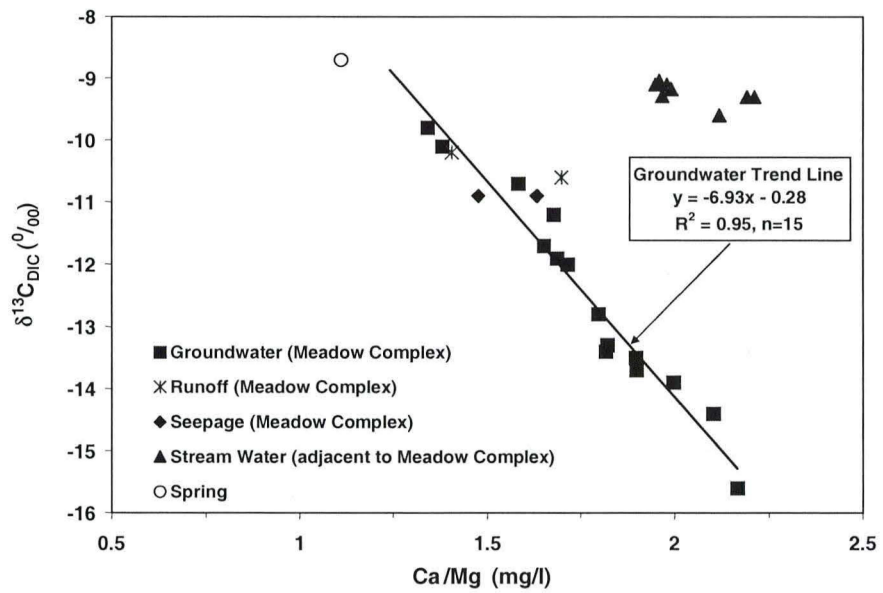

Figure 14. $\delta^{13}C_{DIC}$ vs. Ca/Mg in Shallow Groundwater, Seep and Runoff from the Meadow Complex, Big Creek Stream Water Upstream, Adjacent and Downstream of the Meadow Complex, and a Side Valley Spring.

from the meadow complex, seepage (an adit and the birch seep) stream water upstream, adjacent to and downstream of the meadow complex and a spring (SP-1) located on the valley side wall near the study site (See Fig. 5 for location of spring. The plot shows that as groundwater Ca/Mg ratio increased, the $\delta^{13}C_{DIC}$ decreased. A regression model performed on groundwater data points shows a negative correlation with a good fit (R^2=0.95) at 95% confidence. The plot also shows that runoff and seeps within meadow complex plot close to the groundwater regression trend line, supporting a similar chemical and isotopic evolution. Stream water adjacent to the meadow complex plots away from this line, suggesting a different geochemical and isotopic evolution consistent with previous interpretations.

It was previously suggested based on geochemical and isotopic analyses on a watershed scale that the source of the water feeding Big Creek may have a significant component from the side valley floor seeps. In fact, the spring water shown on the plot had the lowest Ca/Mg ratio and the most positive $\delta^{13}C_{DIC}$ (Fig. 14). The plot also shows that low Ca/Mg water from the side valley is a possible source water in the meadow complex. Thus, as water from the side valley flows through the meadow complex, CO_2 addition from the organic rich meadow substrate initiates additional weathering of carbonate minerals releasing Ca and Mg. The additional CO_2 is responsible for the increases in the DIC, lowering of $\delta^{13}C_{DIC}$ and increase in the Ca/Mg ratio in the shallow groundwater. The fact that stream water from Big Creek plots away from the groundwater trend discounts stream water as a possible source of water for the meadow complex. In addition, the systematic increase of the major ions as Big Creek traverses the meadow complex suggest that shallow groundwater from the meadow augments stream discharge (see Figs. 9 , 10, and 11).

The major ion and DIC data suggest that groundwater locally derived from the side valley is a likely source of water sustaining the meadow complex. The combined major cation-$\delta^{13}C_{DIC}$ analyses support this position and also suggest local groundwater geochemical and carbon isotopic evolution primarily influence by DIC supplied from meadow carbon. Although the age or age distribution of the organic matter in the meadow is not known, it is likely that the most recent (young) organic matter is at or near the surface and older carbon at deeper depths. If the water that sustains the meadow complex is locally derived, and if the DIC input is primarily from the meadow organic matter, then the carbon-14 content of the shallow groundwater should reflect local carbon input.

A plot of C-14 vs. Ca/Mg for select groundwater in the meadow complex and a side valley seep (adit seep) and a spring at higher elevations east of the study area is shown in Figure 15a. The shallow water groundwater was collected from monitoring wells 24, 24b, and 24c (see Fig. 4 for monitoring well location), which represent increasing depths of 70, 170, and 256 cm below ground surface, respectively. The plot shows that as the Ca/Mg ratio increased in the waters, the C-14 content also increased, except for groundwater from monitoring well MW 24. This suggests that addition of modern carbon increased the mineral weathering and the calcium concentration in groundwater. A regression analyses that includes spring water, the seep and deeper groundwater from MW 24B and 24C shows a good fit (R^2= 0.99) at 95 % confidence. If the groundwater flow system at the meadow site can be represented by flow from the side valley, water would flowed from higher elevations (represented by the spring) to lower

elevations (represented by the seep) and through the meadow complex. This scenario is likely as shown in Figure 15a, with increasing PMC as groundwater flows through the meadow complex and to the stream. Shallow groundwater from MW24 plots away from this local C-14 evolution. It is speculated that shallower groundwater at MW 24 does not fit the model trend due to the nature of the hydrologic regime at the study site.

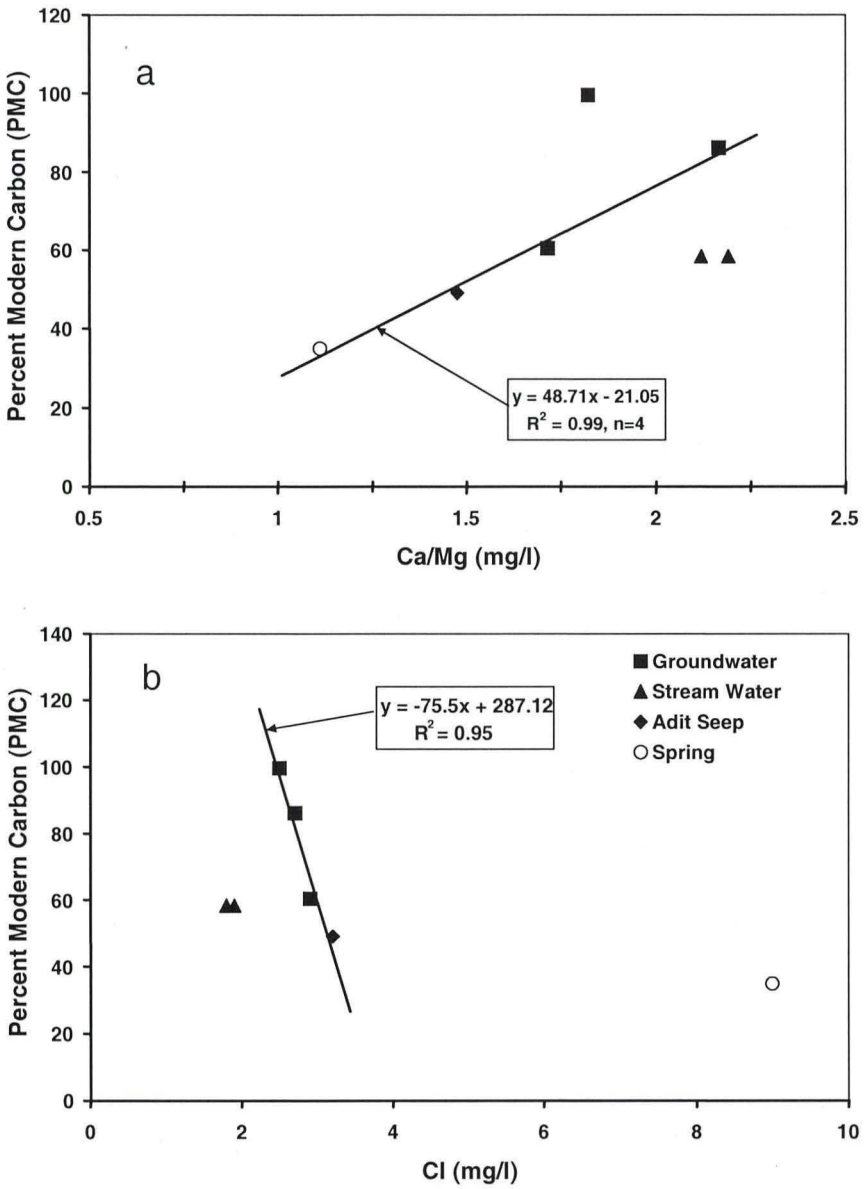

Figure 15. $\delta^{13}C_{DIC}$ vs. ^{14}C (a) and Chloride vs. ^{14}C (b) of Shallow Groundwater and an Adit Seep from the Meadow Complex, Big Creek Stream Water Adjacent to the Meadow Complex, and a Spring from the Side Valley east of the Meadow Complex (see Figs. 4 and 5 for sample locations).

The meadow complex represents a groundwater discharge zone with upward groundwater flow (hydraulic) gradient. This is supported by the increase in Ca in the

shallower groundwater compared to deeper groundwater and the adit seep. It is unlikely that Ca will decrease with depth in a recharge hydrologic regime. The increase in DIC and C-14 in the shallower groundwater resulted from the production of CO_2 in the organic rich sediments at shallower depths. In situ production of CO_2 was responsible for additional mineral dissolution which increased the relative Ca concentration in shallow groundwater. The lower than expected Ca/Mg ratio for water from MW 24 suggests additional local recharge possibly from the upgradient alluvial fan (See Figs. 3 and 4). Local recharge from the upgradient alluvial fan which is poor in organic carbon and dissolved minerals may be mixing with groundwater from the side valley. Recharge from the upgradient alluvial fan appears to flow at shallower depths compared to water from the side valley. Water from the alluvial fan flowing through the upper layers of the meadow sediments rich in organic carbon and poor in mineral will generally have a high C-14 content and low Ca/Mg ratio. Mixing of the local alluvial fan recharge with upwelling deeper groundwater will cause groundwater at the depth of MW 24 to plot towards lower Ca/Mg, and to the left of the C-14-Ca/Mg regression model line.

It should be noted that stream water adjacent to the meadow complex plots away from the C-14-Ca/Mg regression model line towards higher Ca/Mg content. Higher Ca/Mg ratio in stream water compared to most water from the site suggests that stream water can not be a source for the groundwater below the meadow complex. In addition, stream water can not be used to account for the geochemical and carbon isotopic evolution of groundwater at the study site.

Chloride, a conservative tracer can be used along with C-14 to assess the origin of and evolution of meadow groundwater. A plot of Cl vs. C-14 is shown in Figure 15b. The plot shows that stream water and the spring are separated from a local regression trend that includes groundwater and local seepage from the adit seep. The plot also shows that shallow groundwater is poor in chloride and high in C-14 compared to deeper groundwater. The trend line supports the concept of proportional mixing of groundwater from the side valley (similar to the adit seep) with local recharge from the upgradient alluvial fan. Again, stream water upstream and adjacent to the meadow complex does not seem to be a likely source of water to support the meadow complex.

CORRAL CANYON STUDY SITE

The results of analyses of shallow groundwater, seepage and runoff from the meadow complex, seepage from the adjacent side valley and a spring from headwaters of Corral Canyon watershed are presented in Table 4. Although more than one sampling event was conducted at the study site, some sampling locations did not yield sufficient water to analyze for a complete suite of geochemical and isotopic parameters.

General Hydrochemistry

Determining the source of shallow ground water in the meadow complex using major ion chemistry is based on the expected difference in chemical evolution in stream and groundwater systems, and has been previously described for the Big Creek Study area.

To investigate the relationship between shallow groundwater, runoff from the meadow complex, seeps and a spring within the watershed an approach similar to the one used Big Creek was utilized. Cation and anion proportions in water collected in 1999 and

Table 4. Chemical and isotopic analyses of water from Corral Canyon

	SAMPLE ID	Temp (C)	pH	SpC (µS)	NO_3 (mg/l)	Cl (mg/l)	SO^4 (mg/l)	HCO_3 (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	DIC (mg C/l)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
November 1998															
Groundwater	PZ-43	5.3	9.19	6	-	-	-	-	-	-	-	-	22.2	-19.5	-16.4
	PZ-7	7.6	6.81	168	-	-	-	-	-	-	-	-	20.3	-15.5	-16.7
Seep	S-1	8.7	7.00	191	-	-	-	-	-	-	-	-	14.3	-15.6	-16.8
	S-3	8.4	5.99	231	-	-	-	-	-	-	-	-	20.0	-16.3	-16.6
Stream Water	CS-2	2.6	6.97	75	-	-	-	-	-	-	-	-	8.2	-9.9	-16.7
	CS-5	4.3	6.75	168	-	-	-	-	-	-	-	-	6.5	-10.8	-16.7
	CS-6	4.7	6.45	389	-	-	-	-	-	-	-	-	8.9	-11.2	-16.2
July 1999															
Groundwater	PZ-16	14.7	7.20	280	<.02	11.7	9.6	133	25.9	7.3	23.0	6.6	28.7	-17.8	-17.0
	PZ-17	10.4	7.83	250	<.02	12.6	18.8	96	21.3	4.7	19.8	5.8	17.7	-16.8	-17.3
	PZ-18	9.7	7.67	230	<.02	11.3	18.5	103	21.8	4.4	18.6	5.2	18.5	-17.1	-17.7
	PZ-26	8.3	6.96	250	<.02	12.0	17.1	113	26.6	6.1	19.6	5.7	21.9	-19.9	-17.0
	PZ-27A	10.0	7.31	240	<.02	12.2	18.8	90	16.4	4.3	18.2	5.3	15.4	-15.3	-17.0
	MW-1B	11.2	8.92	260	<.02	-	-	103	-	-	-	-	18.5	-16.3	-17.1
	MW-3B	10.9	7.65	240	0.2	12.2	18.8	109	21.4	5.1	20.2	5.7	20.2	-16.4	-17.0
runoff	runoff	24.0	8.35	290	<.02	12.7	8.6	153	25.4	8.7	28.4	7.6	26.2	-15.0	-16.5
Seeps	S-1	10.2	7.46	-	-	12.6	18.8	107	24.4	4.9	20.8	5.7	18.1	-17.3	-17.6
	S-2	10.7	8.02	220	<.02	10.8	16.4	93	15.9	3.7	15.6	4.4	15.7	-16.5	-17.9
	S-3	6.3	8.30	270	<.02	12.2	20.5	110	26.2	4.8	21.0	6.2	19.0	-15.5	-17.1
	S-4	7.9	7.72	240	<.02	12.2	18.8	92	20.7	4.2	16.4	5.1	18.8	-16.9	-17.3
	S-5	9.3	7.01	410	<.02	17.9	34.2	201	38.6	6.7	32.2	9.2	59.2	-11.9	-17.1
	S-6	9.7	8.02	290	<.02	-	-	107	-	-	-	-	18.4	-17.1	-17.2
Stream Water	CS-1	16.3	8.92	240	<.02	-	-	86	-	-	-	-	12.8	-12.1	-17.4
	CS-2	10.8	8.65	230	<.02	11.3	16.8	108	17.0	5.6	19.2	5.8	10.1	-15.0	-17.6
	CS-3	17.2	8.87	230	<.02	10.8	14.7	108	22.5	5.6	19.6	5.8	10.6	-15.0	-17.3
	CS-4	17.5	8.80	270	<.02	12.6	14.7	129	19.1	5.9	22.8	6.3	15.8	-13.0	-17.1
springs	Spring 1	10.8	8.02	190	1.3	9.9	13.7	66	17.8	3.3	12.2	3.6	5.8	-14.5	-17.9
	Seepage	18.7	8.38	260	<.02	-	-	106	-	-	-	-	17.3	-14.7	-16.8
	Spring 2	11.4	7.08	270	<.02	-	-	142	-	-	-	-	31.9	-18.1	-16.9
June- 2000															
Groundwater	PZ-17	15.9	7.10	187	<.02	11.3	21.1	120	23.6	5.1	23.5	5.4	28.3	-14.7	-17.1
	PZ-16	14.3	7.16	138	<.02	7.7	33.1	105	22.4	5.7	23.6	5.6	22.6	-15.8	-17.1
	PZ-27A	15.9	8.21	201	<.02	12.5	14.6	132	25.7	5.0	27.0	5.8	27.5	-15.0	-16.9
	MW-1B*	10.3	6.61	164	<.02	11.2	10.3	107	29.1	5.6	28.7	4.9	23.5	-15.0	-17.3
	MW-2B*	10.7	6.71	846	4.26	27.9	-	607	36.8	22.9	30.0	8.5	79.5	-4.0	-15.6
	MW-3A	10.1	6.84	946	<.02	25.7	1.4	759	84.6	11.2	117.6	26.1	83.6	-12.1	-16.3
	MW-3B*	16.4	6.67	710	<.02	16.6	-	475	28.7	5.0	37.4	7.3	54.8	-13.2	-17.3
Seep	S-1	10.0	7.31	179	<.02	10.9	19.7	108	22.6	4.5	21.6	5.0	23.6	-14.9	-17.0
	S-2	9.6	7.49	137	<.02	8.8	14.5	90	18.5	4.1	16.8	3.7	17.5	-14.2	-17.7
	S-3	8.9	7.09	189	<.02	12.3	22.5	124	25.1	4.7	24.1	5.6	26.8	-14.6	-17.0
	S-4A	8.5	6.90	180	<.02	12.3	28.1	126	23.9	4.3	22.5	5.1	28.1	-15.2	-17.1

Table 4. Continued

	SAMPLE ID	Temp (C)	pH	SpC (µS)	NO_3 (mg/l)	Cl (mg/l)	SO^4 (mg/l)	HCO_3 (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	DIC (mg C/l)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
	S4B	9.7	7.32	185	<.02	12.2	21.7	113	23.9	4.3	21.9	5.0	25.0	-15.1	-17.1
Stream Water	CS-1	13.0	8.01	130	<.02	8.6	15.8	80	17.3	3.0	16.3	3.8	13.3	-8.9	-16.9
	CS-2	13.5	7.69	156	<.02	10.2	17.5	109	21.3	4.7	20.0	4.6	18.1	-12.8	-17.3
	CS-3	17.1	7.90	161	<.02	10.2	18.0	104	21.1	4.4	19.9	4.5	17.3	-11.7	-16.5
	CS-4	15.3	7.46	167	<.02	10.6	19.2	113	22.3	4.3	20.9	4.8	19.0	-11.5	-17.3
	CS-5	16.7	6.64	167	<.02	10.8	19.4	106	22.9	4.5	21.4	4.9	17.5	-11.3	-17.4
	CS-6	16.7	6.65	166	<.02	10.8	19.2	112	22.3	4.3	20.9	4.8	18.8	-11.3	-16.4

SpC = Specific conductance, - = not measured, * = ionic charge balance error greater than 6%

2000 were plotted on a trilinear diagram (Fig. 16). Three groundwater samples from the meadow complex which had charge balance errors of 6% or more were excluded from this analysis.

In general, water from study site and the watershed is represented by the cations Ca, Na, and K, and anions HCO_3 and SO_4. The cation facies had about 50-60% Ca 40-50% Na + K, and 20-30% Mg. The anion facies was about 20-30% Cl, 80-90% SO_4 and 60-95% HCO_3^-. The waters can be classified as a mixed cation-HCO_3 type.

There are no obvious differences between cation and anion proportions between shallow groundwater, runoff from the meadow complex, seeps collected from the adjacent side valley near the meadow complex and the spring sampled at the headwater of the watershed (Fig. 16). The trilinear diagram shows that the most variation in the water samples was associated with the bicarbonate content (70 – 95%). The anion-cation proportions shown in the trilinear diagram suggest that the waters in the meadow complex and the watershed are undergoing similar geochemical evolution. The major ion data can be used to suggest that there is no difference in the source of water between the stream and the shallow groundwater in the meadow complex.

Source of Water in Corral Canyon Watershed

Stable oxygen isotopes for 46 water samples collected in November, 1998, July, 1999 and June 2000, ranged from –17.9 to –15.6 $^0/_{00}$, with a mean of -17.0 $\pm$ 0.5 (Table 4). The $\delta^{18}O$ values of these samples which included stream water, shallow groundwater, seeps and a spring from Corral Canyon are similar to values reported for this part of the Great Basin (Davisson et al., 1999). The $\delta^{18}O$ value of spring water and mean $\delta^{18}O$ values for seeps, shallow groundwater and runoff from the meadow complex, stream water are shown in Figure 17. The spring at the headwater of the watershed had the lightest $\delta^{18}O$ value of -17.9 $^0/_{00}$. The $\delta^{18}O$ of spring water from the upper regions of the watershed can be assumed to represent recent snow melt, since snow pack volume was greatest in this region. This is the likely cause of the lower $\delta^{18}O$ value and the statistical difference from other samples. There is no statistical difference between the mean oxygen isotopic values for seeps, shallow groundwater within the meadow complex and stream water. The standard deviation for seeps, groundwater and streams are similar

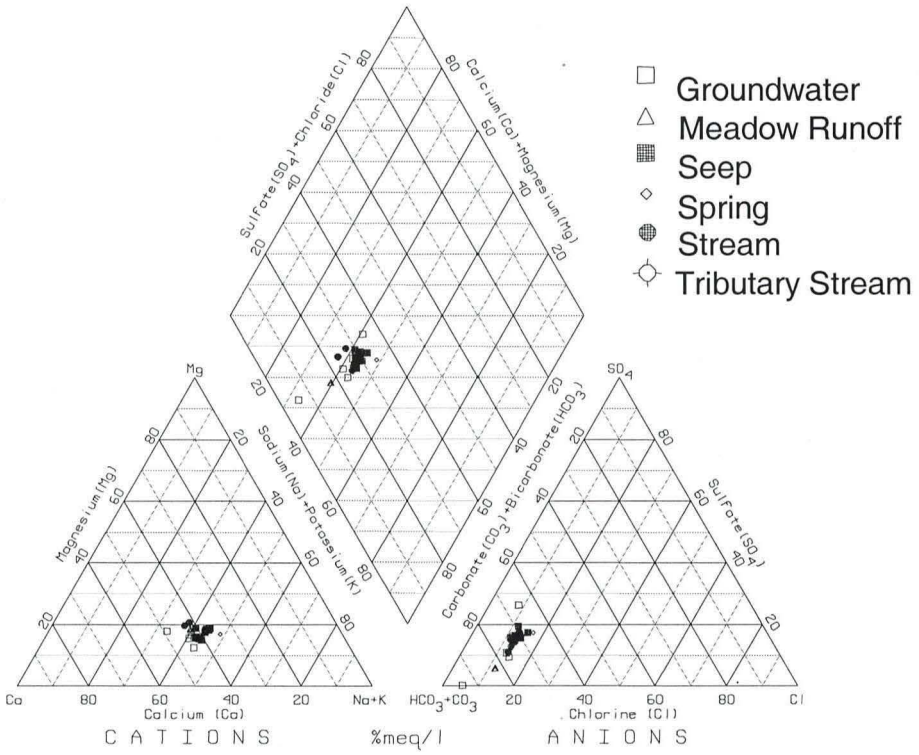

Figure 16. Chemical Composition of Water from the Corral Canyon Watershed.

(0.4, 0.5 and 0.4 $^{0}/_{00}$ respectively). However, the range in the oxygen isotopic values are higher for groundwater ($2.1^{0}/_{00}$) compared to seeps (1.3 $^{0}/_{00}$) and stream water ($1.4^{0}/_{00}$). The high standard deviation for seeps, groundwater and stream water, which is much higher that the precision of the measurement technique argues for either different sources of water. Seasonal recharge, the difference in the residence time of water flowing through different pathways in the watershed or secondary enrichment processes may account for the observed differences. It is notable that water samples collected during November 1998 are about $0.5^{0}/_{00}$ heavier that those collected in July 1999 and June 2000 (Table 4). On close examination, the oxygen isotopic value for groundwater locations that were sampled more than once (July 1999 and June 2000) showed no significant difference relative to the precision of the measuring technique.

Seeps within the meadow complex sampled more than once (1998, 1999 and 2000) showed significant variation in their oxygen isotopic values. The oxygen isotopic values for seep S-1 was 16.6 $\pm$ 0.9 $^{0}/_{00}$ with a range of $1.7^{0}/_{00}$ (n=3), seep S-2 was -16.4 $\pm$ $0.3^{0}/_{00}$ with a range of 0.3 $^{0}/_{00}$ (n=2), and seep S-3 was -15.5 $\pm$ 0.9 $^{0}/_{00}$ with a range of $1.7^{0}/_{00}$ (n=3) (see Fig. 6 for sample locations). In addition, seeps from the south valley wall were much heavier (-11.9 and $-17.1^{0}/_{00}$). Differences in the variation in the oxygen isotope values for seeps may either point to differences in source of water or different degree of evaporation of snow during melting and prior to recharging the groundwater system. Also, if seeps within the meadow complex are considered as a proxy of groundwater supply to the meadow, the variation in the isotopic values or S-2 and S-3 suggest different sources of groundwater feeding the meadow.

The variation in the oxygen isotopic results may reflect a complicated hydrologic system below the meadow complex and the entire watershed. Previous hydrometric and stratigraphic studies conducted at the study site have documented more than one aquifer with a complicated groundwater flow system that is seasonally variable in both the upper and lower aquifers (Miller and Jewett, 2000). Water level monitoring from shallow and deeper piezometers suggest that the lower aquifer at the site may be confined at some locations, semi-confined, or unconfined at other locations (Miller and Jewett, 2000). It is also important to note that while the $\delta^{18}O$ of groundwater in the meadow complex from locations sampled for more than one season did not vary, the $\delta^{18}O$ of seeps within the meadow complex varied significantly and may in part be explained by variable groundwater input upgradient of the meadow complex and locally from the alluvial fans.

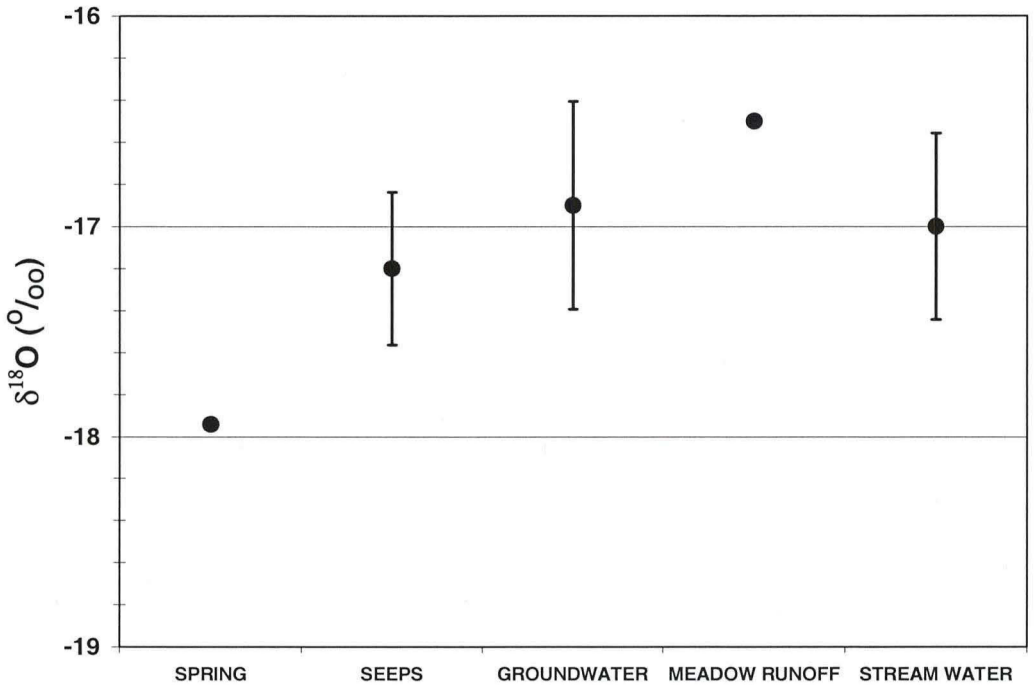

Figure 17. Distribution of $\delta^{18}O$ in Selected Water Samples in the Corral Canyon Watershed.

The mean stable oxygen isotopic values of stream water and groundwater at the study are similar. Stream discharge from headwater through the study site was not significant. Large cavities in the volcanic rocks were observed in the watershed upgradient of the meadow complex in a reconnaissance survey. If these cavities are prevalent and interconnected, they may be responsible for channeling snowmelt into the subsurface, since there was no significant channel development or streamflow in the watershed above the study site. The valley bottom at the Corral Canyon study site is broad compared to that of Big Creek. The absence of significant streamflow within this broad valley argues for transport of snowmelt in the upper portions of the watershed via subsurface flow. It was noted that the valley gradient at the meadow complex was much lower compared to up and downstream locations. The lack of significant stream flow into the meadow complex and significant augmentation of stream flow below the site argues for a groundwater source in the meadow complex. In fact, discharge measurements showed a more that 4 fold increase in stream flow at station CS-6 below

the site (Bob Barr, 2000, Personal Communication). Miller and Jewett, (2000) suggested that groundwater was an important, if not the only source of water in the meadow complex using hydraulic gradients from piezometric data. Groundwater from the meadow complex may be responsible for the increased stream discharge below the study site. Compared to oxygen isotopic analyses from the Big Creek Meadow complex, the oxygen isotopic data from Corral Canyon can not be used to exclude possible out-of-basin groundwater as a possible (although not likely) or additional source of water to the meadow complex.

Chemical and Isotopic Evolution of Water in Corral Canyon Meadow Complex

Weathering reactions responsible for the major ion chemistry in carbonate aquifers was discussed in section dealing with the Big Creek Meadow complex. Corral Canyon watershed has volcanic rocks, thus the expected changes in DIC and $\delta^{13}C_{DIC}$ will not involve significant amounts of carbonates. However, the same concept of geochemical and isotopic evolution will be applied in analysis of water from this study site.

The major cation proportion for water in the study area is dominated by Ca and Na + K (see Fig. 16). Thus, to understand local geochemical and carbon isotopic evolution of groundwater in the Corral Canyon meadow complex, $\delta^{13}C_{DIC}$ was plotted against Ca/Na (Fig.18). Also shown on the plot are samples of runoff from the meadow complex, seepage in the meadow and side valley, stream water and a spring from the headwater region of the watershed. It should be noted that one groundwater sampling location was not include in this analysis. The sample collected from MW 2B (see Fig. 6) had a $\delta^{13}C_{DIC}$ value of -4.0 $^{0}/_{00}$ suggestive of methanogenic conditions at this location (e.g., Barker and Fritz, 1981; Clark and Fritz, 1977). It is speculated that this methanogenic conditions that occurred in June of 2000 was related to lower groundwater input in this portion of the meadow complex. This well is located in a region of the meadow complex considered to be a "raised bog" which may be hydrologically isolated from the rest of the system. Alternatively, the DIC in the water from MW 2B could have been the result of closed system dissolution from Co2 derived from C-4 vegetation (Clark and Fritz, 1997, Cane and Clark, 1998). This conclusion is not likely since most of the groundwater sampled in the meadow complex did not exhibit such isotopic behavior.

Excluding data from MW 2B, the plot shows that as shallow groundwater Ca/Na ratio increases, the $\delta^{13}C_{DIC}$ increases. A regression model of groundwater data show a positive correlation with a good fit (R^2=0.88) at 95% confidence. In general, the model line shows that as groundwater evolved (towards more positive $\delta^{13}C_{DIC}$ values), the Ca/Na ratio increased, suggesting longer residence time for groundwater and greater mineral weathering in the aquifer (e.g. Fritz et al, 1978). The plot also shows that runoff from the meadow and seeps within meadow complex plot close to the groundwater regression model line, supporting a similar chemical and carbon isotopic evolution.

Some stream water from the site plot close to the groundwater regression model line while others do not (Fig. 18). As the stream water flowed through the study site in July 1999, stream flow was significantly augmented by groundwater discharge causing stream water chemistry to lie along the groundwater trend. Stream water samples that

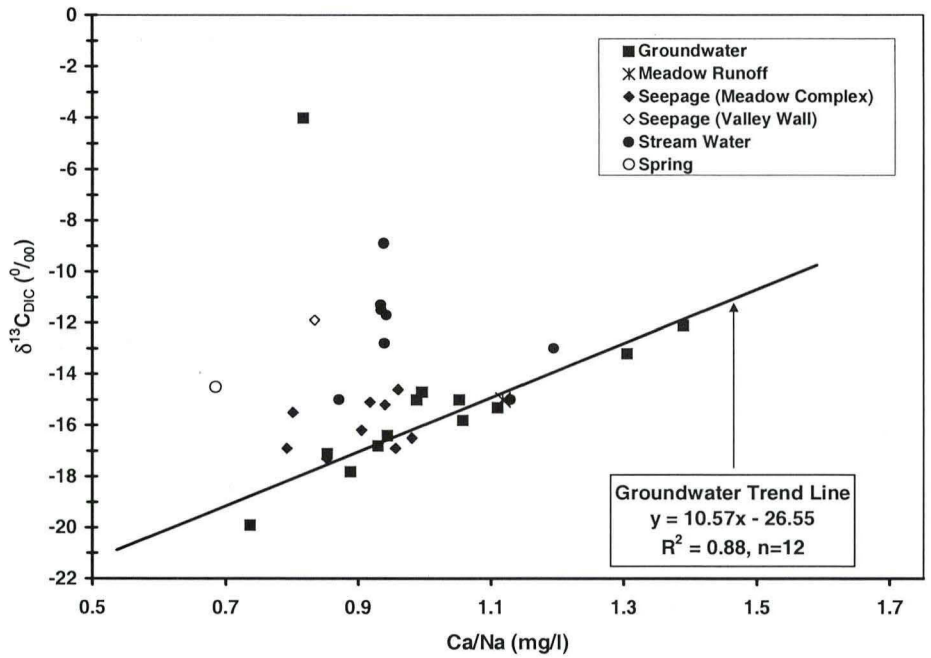

Figure 18. $\delta^{13}C_{DIC}$ vs. Ca/Na in Shallow Groundwater, Seep and Runoff from the Meadow Complex, Corral Canyon stream water from Upstream, Adjacent and Downstream of the Meadow Complex.

plot away from the groundwater trend were mostly samples collected in June 2000 and upgradient of the site in June 1999. Hydrologic conditions at the study site in June 2000 were significantly different from previous years. In June 2000, groundwater levels in the meadow complex were lower than in the previous sampling seasons in November 1999 and July 1999. There was no runoff from the meadow complex into the stream in June 2000. In addition, surface material at the site was less saturated compared to the previous years. In the absence of groundwater discharge into the stream segment through the site, the geochemistry and carbon isotopic character of stream water in June 2000 was derived from upstream of the meadow site.

Figure 18 shows that there was more variation in the $\delta^{13}C_{DIC}$ of stream water compared to the Ca/Mg ratio. This observation can be explained if the DIC in stream water was derived from C-4 vegetation. Alternatively, the interaction of stream water with atmospheric CO_2 prior to flowing through the study site will cause preferential loss of ^{12}C relative to ^{13}C resulting in a positive shift in the $\delta^{13}C_{DIC}$. The spring water sampled in the upper reaches of the watershed and several of the seeps from the meadow complex plot above the groundwater model line, suggesting a similar source of heavy carbon in these waters. Since the springs and seeps have a groundwater source, their DIC evolution might involve a mixture of CO_2 from C-4 vegetation in the recharge areas at higher elevations and CO_2 from C-3 vegetation in the valley bottom. Carbon isotopic analyses in a similar arid setting in southern Nevada show waters with similar isotopic characteristics (White and Chuma, 1987). The variation in the $\delta^{13}C_{DIC}$ character for potential sources of water (seeps) to the meadow complex may be related to the hydrologic complexity within the watershed and the study area.

Water from the upper 1m in sediments from Corral Canyon meadow complex was not sampled because only the deeper piezometers in more permeable sediments were able to yield water in sufficient quantities. This may be due in part to the limitations of slotted piezometers and monitoring wells in sampling materials with low hydraulic conductivity in the upper 1m. Thus it was not possible to compare the shallow groundwater geochemistry with seeps and springs adjacent to the study site. It was not also possible to conduct spatial analyses of stream evolution similar to the Big Creek Study area. This was because of the low discharge characteristics of the Corral Canyon stream and the absence of flow in the upper portions of the watershed. However, groundwater elevation observations in the meadow complex suggest a discharging regime supported by artesian conditions and groundwater seeps in the meadow complex (Miller and Jewett, 2000). Groundwater elevation maps showed that the water table sloped towards the stream channel (Miller and Jewett, 2000). The major ion chemistry coupled with DIC data suggest that groundwater was the dominant source of water that supported the wet meadow vegetation at the Corral Canyon. The hydrometric and geochemical evidence can be used to argue for groundwater as the only source for water for the wet meadow complex.

CONCLUSIONS

Geochemical and stable isotopic survey of shallow groundwater from a high altitude meadow complexes in Big Creek and Corral Canyon, Central Nevada suggest that groundwater was the dominant source of water supporting the meadow complexes. The oxygen isotopic data showed that all water within the watershed was derived from local snowmelt.

In Big creek, data from study suggest that the sources of water that supports the meadow complex are locally derived from groundwater flowing in the side valley and recharge from an upgradient alluvial fan. The results also suggest that in Big Creek, stream water is not a source of water for the messic and wet meadow portions of the meadow complex, although short term high stream discharge may provide temporal recharge of the upgradient alluvial fan.

In Corral Canyon, the result of this and other studies suggest a hydrologically complex setting. However, the data from this study suggest that shallow groundwater at the meadow complex is derived entirely from groundwater, perhaps from the lower artesian aquifer. This lower artesian aquifer probably has its source in the alluvial valley and/or from local recharge alluvial fans at the site. The results also showed that during periods of high groundwater levels, stream water had a similar chemical and isotopic character as groundwater, suggesting groundwater recharge of the stream, rather than stream recharge of the meadow groundwater.

It should be noted that it was not possible to quantify the relative contribution of stream and groundwater in the meadow complexes. This because the results of the study show that groundwater was the exclusive source of water supporting the meadow complex.

There are several vegetative communities of the meadow complexes tend to reflect the long term hydrologic condition at the site. Even though this study was

conducted over a short term period, the results strongly support a groundwater source for the meadow complexes. Stream diversions and other hydrologic manipulations in the watershed can still have profound consequences for the survival of meadow ecosystems. Although not directly investigated in this study, meadow groundwater-stream water dynamics are important in controlling the depth of groundwater with the meadow complexes. Because of the delicate and dynamic balance between stream discharge (stage) and groundwater levels, reduction of stream stage through diversion or other hydrologic manipulation will depress the elevation of the "dynamic boundary" between meadow groundwater and stream water. This will result in lowering of the water table level in the meadow complex (in order to establish a new equilibrium). The degree to which the stream water-groundwater boundary is lowered will determine the impact on the groundwater level in the meadow complex and the degree to which meadow vegetation will be affected over the long term. It is likely that the impact from lower groundwater levels will be greater in the wet and mesic meadow vegetation.

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